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Using Artificial Orthographies for Studying Cross-Linguistic Differences in the Cognitive and Neural Profiles of Reading

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Abstract

Reading and writing are cultural inventions that have become vital skills to master in modern society. Unfortunately, writing systems are not equally learnable and many individuals struggle to become proficient readers. Languages and their writing systems often have co-varying characteristics, due to both psycholinguistic and socio-cultural forces. This makes it difficult to determine the source of cross-linguistic differences in reading and writing. Nonetheless, it is important to make progress on this issue: a more precise understanding of the factors that affect reading disparities should improve reading instruction theory and practice, and the diagnosis and treatment of reading disorders. In this review, we consider the value of artificial orthographies as a tool for unpacking the factors that create cognitive and neural differences in reading acquisition and skill. We do so by focusing on one dimension that differs among writing systems: grain size. Grain size, or the unit of spoken language that is mapped onto a visual graph, is thought to affect learning, but its impact is still not well understood. We review relevant literature about cross-linguistic writing system differences, the benefits of using artificial orthographies as a research tool, and our recent work with an artificial alphasyllabic writing system for English. We conclude that artificial orthographies can be used to elucidate cross-linguistic principles that affect reading and writing.

Keywords

writing systems; artificial orthographies; grain size; mapping principle; syllables

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1. Introduction

In the timeline of human evolution, reading and writing are relatively new inventions, but they have become vital skills to master in modern society. Unfortunately, writing systems were not created equal and many people struggle to become proficient readers. Furthermore, the cognitive manifestations of reading disorders and their neural signatures also vary by writing system. In this review we will discuss the diversity of the world's writing systems, some of the factors that may account for differences in the learnability of these systems, and experimental approaches for investigating the role of these factors in reading acquisition and skill. Cross-linguistic comparisons are a logical way to study the diversity of the world's writing systems. We will discuss the strengths and weaknesses of using cross-linguistic comparisons, and highlight the use of artificial orthographies as a more recent methodology that can help advance the field.

1.1 Writing Systems Are Not Equal

There is mounting evidence that writing systems are not equally easy to learn. One of the clearest demonstrations of this finding has come from the comparison of alphabetic writing systems that vary in their phonological/orthographic consistency. Phonological consistency refers to the degree to which each symbol has one and only one phonological mapping. It has been primarily studied in the context of alphabetic writing systems, though this definition can be applied to non-alphabetic systems as well (Lee, Tsai, Su, Tzeng, & Hung, 2005; Yang, Zevin, Shu, McCandliss, & Li, 2006). Other terms that are used interchangeably to refer to phonological consistency are ‘shallow or transparent orthography’ for phonologically consistent writing systems and ‘opaque or deep orthography’ for phonologically inconsistent ones. Serbo-Croatian is an example of a perfectly consistent alphabetic orthography, with one-to-one grapheme to phoneme correspondences. In contrast, English is at the other end of the spectrum, with complex mapping patterns: most letters can represent more than one sound (the letter g makes a different sound in ‘gem’ ‘game’ and ‘tough’), and most sounds can be represented in more than one way (the vowel sound /u/ is represented differently in the words ‘view’, ‘to’, ‘through’, ‘shoot’, and ‘lute’).

There has been extensive research showing that phonological consistency affects learning rates and the acquisition of phonological awareness (Ellis & Hooper, 2001; Patel, Snowling, & de Jong, 2004; Spencer & Hanley, 2003; Ziegler, Perry, Jacobs, & Braun, 2001). For example, children learning English struggle to reach 90% accuracy on nonword reading after 4-5 years of instruction. In comparison, children learning Finnish, a phonologically consistent alphabetic system, reach 90% after 10 weeks of instruction (Goswami, Gombert, & De Barrera, 1998; Ziegler & Goswami, 2005). Furthermore, dyslexia is manifested differently and at higher rates in readers of inconsistent versus consistent alphabetic systems (Everatt & Elbeheri, 2008; Goulandris, 2003; Ziegler & Goswami, 2005). For example, in English slow and inaccurate nonword reading is a hallmark symptom of dyslexia. In more consistent writing systems, like Italian, slow word reading and poor performance on rapid naming tasks are more likely to serve as diagnostic markers. Phonological consistency has also been shown to modulate neural networks involved in reading. For example, readers of Italian, a phonologically consistent language, show greater activation in a left superior temporal region associated with speech-based phonological processing during word reading, as compared to readers of English (Bolger, Perfetti, & Schneider, 2005; Paulesu et al., 2000).

A second demonstration that writing systems are not equally easy to learn comes from comparisons of orthographies that differ in their fundamental mapping principle (see Figure 1). Different languages map differently-sized units of spoken language onto visual graphs. Alphabets use a phonemic grain size, such that in a perfectly consistent alphabet each letter represents a single phoneme. In syllabaries, like Kana used in Japan, a syllable unit is mapped onto each visual unit. Somewhere in between are alphasyllabaries, like those used to represent many languages in India and Ethiopia. For these systems, each visual unit represents a whole syllable but phonemic sub-components are visually identifiable within the graphs. Lastly, in logographic systems, a whole word or morpheme is mapped onto a visual unit, such as a character in the Chinese writing system.

Readers of non-alphabetic systems will generally need more time to learn the visual graphs of their writing systems, because the graph inventory will increase as the grain size of the writing system increases. For example, it takes readers of Chinese years to learn the foundational 3000 characters that are needed to become a proficient reader (Carson, 1992; Cheung & Ng, 2003). Readers of alphasyllabaries, like Kanada or Marathi, similarly take years to master all of the visual-phonological mappings within their writing systems. The visual-phonological mappings of alphabets, with 25-35 graphs are typically learned pre-literacy (Ehri, 1999). In a highly consistent alphabetic system, this knowledge can allow beginning readers to sound out, or “decode,” a large number of words within an initial year of formal reading instruction. On the other hand, readers of less consistent alphabetic systems still require years of practice to become highly fluent at visual word recognition.

The frequency and profile of reading disabilities also varies across writing systems that use different grain sizes for mapping between orthography and phonology (see Figure 2). The predominant view in the literature is that the core deficit in dyslexic readers of alphabetic languages has to do with phonological awareness (Bruck, 1992; Snowling, 1998; Snowling, 1981). Phonemic awareness more specifically has been shown to be a good predictor of reading skill (Hulme et al., 2002; Snowling, 1981). Phonological deficits are also thought to be a primary deficit in reading disorders of alphasyllabic writing systems (Nag & Snowling, 2011), but children with poorer visual processing skills are also at heightened risk for poor reading achievement. The contrast is even more marked in the Chinese writing system, which uses a logographic mapping principle. In Chinese, the primary deficits in dyslexia are thought to reflect visual/orthographic (Ho, Chan, Lee, Tsang, & Luan, 2004; Ho, Chan, Tsang, & Lee, 2002) and morphological (Shu, McBride-Chang, Wu, & Liu, 2006) risk factors, rather than a fundamental deficit in phonological awareness. In addition, writing deficits (Tan, Spinks, Eden, Perfetti, & Siok, 2005) are thought to play a larger role in Chinese reading impairments.

Lastly, writing systems that use different grain sizes for mapping between orthography and phonology have also been associated with differences in the neural networks for reading. In their meta-analysis, Bolger and colleagues found greater left superior temporal gyrus activation in English/Western European alphabetic writing systems and greater right fusiform gyrus activation in logographic Chinese (Bolger et al., 2005), although this finding remains a topic of debate (Mei et al., 2012; Tan, Laird, Li, & Fox, 2005; Tan et al., 2001). Alphasyllabaries, with approximately 37 active scripts used by over 100 different languages (omniglot.com), were not included in these prior reviews. Thus, it remains largely unknown whether they impose a distinctive character on the neural networks for reading, although recent findings suggest that alphasyllabary reading engages typical cortical areas involved in both alphabetic and syllabic writing systems, such as left superior temporal gyrus and left inferior and superior parietal gyri (Das, Bapi, Padakannaya, & Singh, 2011; Das, Kumar, Bapi, Padakannaya, & Singh, 2009).

1.2 Challenges of Cross-linguistic Research

Past research has made substantial progress in describing the many dimensions, or design principles, by which writing systems vary (Perfetti & Harris, 2013). In addition to phonological consistency and grain size, writing systems vary along many other dimensions that have been shown to affect learning. For instance, it is harder to learn writing systems that are more visually complex, less semantically transparent, or that represent a more syllabically complex spoken language (Frost, 2012; Pelli, Burns, Farell, & Moore-Page, 2006; Seymour, 2003). Because each of the world's writing systems represents a unique position in a complex multi-dimensional space, it is challenging to determine the impact of a given dimension on learnability. However, the impact of some dimensions are inherently easier to study than others using cross-linguistic comparisons (Katz & Frost, 1992; Seymour, 2003). For example, it is easier to study a dimension if it is possible to isolate it by comparing two or more languages that are minimally different (i.e., they only differ in one dimension). With that in mind, studying phonological consistency using cross-linguistic comparisons has been quite productive because there are many languages that are minimally different with the exception of phonological consistency (e.g., English and Welsh).

In contrast, it is more difficult to cleanly compare writing systems that have different mapping principles because many dimensions co-vary with grain size. For example, writing systems that use larger grain sizes for orthographic-phonological (O-P) mapping tend to be more visually complex than those that use a smaller grain size (Changizi & Shimojo, 2005; Pelli et al., 2006), and they tend to represent spoken languages with predominantly simple (e.g., consonant-vowel) syllabic inventories (Perfetti & Harris, 2013). Many reading scholars have described in depth the complexity involved in cross-linguistic comparisons of writing systems (Katz & Frost, 1992; Perfetti & Harris, 2013; Wydell, 2012; Wydell & Butterworth, 1999; Ziegler & Goswami, 2005, 2006), all making similar observations that grain size and other factors are not orthogonally related. Another issue that complicates any cross-linguistic comparison is that it is quite difficult to control for sociocultural differences across languages, such as terms of instruction, teacher quality, availability of resources, and student motivation (Ziegler & Goswami, 2006). All of these factors certainly affect learning outcomes, independent of how they may interact with the characteristics of a given writing system and the spoken language it represents.

2. The Value of Artificial Orthographies in Understanding Effects of Grain Size

A handful of investigators have turned to artificial orthographies – in which specially created or "borrowed" graphs from an unknown writing system are mapped onto a naturally occurring spoken language – as a tool for studying writing system differences in laboratory settings. Artificial orthographies allow researchers to minimize problems of covariance, inherent to any cross-linguistic study, by being able to control overall statistics and characteristics of each design dimension, and thus allowing greater precision for interpreting results. For example, controlling the statistics of phonological consistency or visual/perceptual complexity are prime candidates for an effective way to use artificial orthographies to study reading. Artificial orthographies also enable controlling for exposure and experience of each participant that is never truly controlled for in studies using naturally occurring writing systems, but could potentially affect item-specific individual differences (Share, 1995). We have identified 13 published studies, in addition to ongoing work in our lab (Hirshorn et al., 2012; Hirshorn et al., 2013; Moore, Durisko, Chen, et al., 2013), that have used artificial orthographies (Bitan & Booth, 2012; Bitan & Karni, 2003, 2004; Bitan, Manor, Morocz, & Karni, 2005; Gleitman & Rozin, 1973; Hart & Perfetti, 2008; Maurer, Blau, Yoncheva, & McCandliss, 2010; Mei et al., 2012; Moore, Brendel, & Fiez, 2014; Moore, Durisko, Perfetti, & Fiez, 2013; Sebesta, 1964; Taylor, Plunkett, & Nation, 2011; Yoncheva, Blau, Maurer, & McCandliss, 2010). They cover topics such as the acquisition of visual expertise (Maurer et al., 2010) or visual/perceptual role in neural processing of reading (Moore, Durisko, Chen, et al., 2013; Moore, Durisko, Perfetti, et al., 2013), effect of letter instruction on word identification (Bitan & Booth, 2012; Bitan & Karni, 2003, 2004; Bitan et al., 2005), phonological interference in lexical representations (Hart & Perfetti, 2008), orthographic consistency (Sebesta, 1964; Taylor et al., 2011), and differences in learning and the neural representations of reading as a factor of grain size (Gleitman & Rozin, 1973; Hirshorn et al., 2013; Mei et al., 2012; Moore et al., 2014; Yoncheva et al., 2010). Studies have varied in the method of instruction, design of orthographies (statistics or visual characteristics) and methodologies (i.e., behavioral, fMRI, ERP, neuropsychological), depending on the specific questions regarding learning or neural consequences of writing system dimensions (see Table 1). Artificial orthographies may be especially useful for studying grain size, because you can create and compare systems where the spoken language is held constant, and thus control for many of the dimensions that would co-vary using naturally occurring writing systems. Here we will further review the relevant body of work through the lens of grain size.

Thus far, we have discussed grain size in terms of the O-P mapping principle by which unit of spoken language is mapped onto a visual graph. In the discussion below, we consider how artificial orthographies can be used to study this aspect of grain size. Additionally, we will consider two other aspects of grain size: the grain size of the instructional unit that is used for teaching, and the grain size of the internal orthographic and corresponding phonological representations that are used to decode printed words (see Figure 3). These alternative perspectives on grain size can be orthogonal to the mapping principle that is used for a given writing system. For example, reading instruction for alphabetic writing systems can involve attention to syllable-level mappings, and skilled word recognition in alphabetic writing systems may involve suprasegmental internal representations.

Our inclusion of these additional perspectives on grain size is driven in part by a secondary aim of this review, which is to highlight possible benefits of syllable representations in reading. Several researchers have made the claim that the syllable-level of representation is more advantageous for beginning readers. It is more psychologically accessible, as syllable awareness is developed independent of reading skill and is present even in pre-literate readers, as opposed to phoneme awareness, which is thought to develop at least in part through reading experience (Anthony & Francis, 2005; Leong & Haines, 1978; Liberman, Shankweiler, Fischer, & Carter, 1974; McGuinness, McGuinness, & Donohue, 1995). Syllables are easy to pronounce compared to phonemes, which are more abstract and difficult to produce or identify in isolation. Syllables are also more intuitively easy to combine and blend to make a new word (e.g., /le/ + /di/ = lady), whereas blending phonemes requires more abstract manipulation to blend isolated phonemes (e.g., ‘kuh’ + ‘ee’ + ‘puh’ = keep). Therefore, we are interested in exploring the possible utility of syllabic representations instead of phonemic representations in writing systems.

2.1 The Grain Size of O-P Mapping and its Impact on Reading

In terms of studying grain size from the perspective of mapping principle differences across writing systems, there is a rich history of comparing alphabetic and logographic writing systems (Perfetti & Harris, 2013). This is partly because such systems are maximally contrastive and therefore a good place to begin investigation. It is also the case that the strongest traditions of psycholinguistic research have tended to emerge from countries with alphabetic writing systems, and this has helped to provide a rich linguistic understanding of alphabetic writing systems and key dimensions that characterize their learnability. While many of the world's writing systems use a syllabic or alphasyllabic mapping principle, such writing systems have received comparatively little study.

Limited past research has explored how O-P mapping at the syllabic level can influence learning. An important study comparing the impact of grain size comes from a cross-linguistic comparison of two highly understudied African languages (Asfaha, Kurvers, & Kroon, 2009). This study compared children in Eritrea, who were learning to read one of four African languages with similar syllabic structure and complexity (see Figure 4). Due to socio-cultural influences, two of the four languages are written using an alphasyllabic script (Ge'ez) and two are written using an alphabetic script (Latin). Other factors that might impact learning – such as the linguistic structure of the spoken language, educational traditions of a given country, or socioeconomic background of the children – were relatively similar across the studied groups. When children's spelling and word learning between writing systems was compared, the investigators found higher performance for children learning a writing system based on the Ge'ez alphasyllabary, compared to a writing system based on the Latin alphabet. They noted some evidence for an initial disadvantage for Ge'ez script learners, due to the larger graph inventory associated with this script as compared to the Latin alphabetic. However, any initial disadvantage was counteracted by easier blending of larger grain size units. In other words, children found it easier to blend together a sequence of syllables to recognize a printed word, as compared to a string of phonemes.

The findings of Asfaha et al. (2009) are consistent with a variety of evidence suggesting that the phoneme-based level of representation, which is a defining property of alphabetic writing systems, is a particularly challenging unit of analysis for beginning readers. In fact, this issue motivated some of the original work using artificial orthographies. Specifically, Gleitman and Rozin (1973) developed a proto-syllabary for English using a combination of images and text, based upon the idea from speech perception research that the syllable is a more natural unit of phonological analysis for children than the phoneme. However, due to the complex syllable structure of English, which would require thousands of graphs to uniquely represent all of the syllables of English, they taught a 23-graph syllabary and only tested a small set of words and sentences. They found that kindergarten-aged children who were taught using a syllable-based method were better than controls at blending untaught combinations of syllables to form new multisyllabic words (e.g., can + dee = candy). Despite the small scope of the artificial orthography, they reasoned that it could function as a valuable transitional orthography for English, because it used a more accessible grain size (the syllable) to expose children to the basic concepts of orthographic representation and phonological decoding.

Although the work of Gleitman and Rozin (1973) was successful, their scope was small and they did not address effects of grain size on reading fluency or comprehension, per se. Our research group has developed two artificial writing systems for English that use different grain sizes for O-P mapping. By developing writing systems that can represent any English word, we have been able to study how various dimensions affect the learnability of a writing system, as measured in the context of single word processing and in the reading of connected text for meaning, with cumulative exposure to a corpus of more than 500 words. In contrast, all previous studies have used only single word exposure involving a small corpus of ~ 50 words or less.

We began our work with artificial orthographies by developing a phonologically consistent alphabet for English. Faces were used as the visual graphs, because one of our initial goals was to examine the effects of perceptual demands on orthographic representation. For the alphabetic ‘Facefont’, each face represents a single phoneme. Subsequently, we developed an alphasyllabary for English. In this system, termed ‘Faceabary,’ each face represents a syllable, with the face identity mapped onto the consonant part of the syllable and the facial emotion mapped onto the vowel (Figure 4).

The development of Faceabary involved a number of decision points about how to represent such a syllabically complex languages as English. English is estimated to have more than 10,000 unique syllables, although precise counts vary due to speaker variation and where syllable boundaries are placed. This makes it impractical to represent each unique English syllable with a single graph. As an alternative, we borrowed and extended design features that can be found in naturally occurring alphasyllabaries. For instance, most alphasyllabic scripts are mainly comprised of graphs that represent CV syllables, which can accurately represent spoken words that contain one or more CV syllables, but not words within the spoken language that have other syllabic structures (e.g., CVC, CCV). One common solution is to combine two graphs, in a sequence or in some type of combined visual form, with the vocalic content of one graph suppressed as part of the decoding or word identification process. We found in pilot testing that readers could readily use vocalic suppression to blend together a sequence of Faceabary graphs to represent complex English syllables. For example, “glad” could be decoded from a three-graph sequence representing the syllable sequence “guh”, “la”, and “duh”. However, we also discovered limits on the effectiveness of this design principle. Individuals were poor at suppressing two or more successive vowels in a sequence, and vowel suppression worked poorly for stop-consonant clusters. To overcome these limitations, we created a set of 265 faces that represents CV English syllables through systematic combinations of face identity and expression, and a secondary set of 110 faces that represent a selected set of 36 VC syllables, 35 CCV syllables, 22 VCC syllables, and 13 simple V syllables. This secondary set also contains 4 graphs for marking verb inflections, plurals, and possessives, because morphological content adds to the phonological complexity of English syllables. Interestingly, primary and secondary graph sets are found in many alphasyllabic scripts, largely in response to the need to represent syllables in the spoken language that have consonant cluster onsets or codas. Thus, the exercise of creating an alphasyllabary for English highlighted common design challenges associated with mapping orthography to phonology at the syllabic grain size and cognitive constraints that may impact the decoding of words with complex consonant clusters.

By comparing the learning of Faceabary with the learning of Facefont, we have been able to explore the idea that any two writing systems that use different grain sizes for O-P mapping naturally have tradeoffs between the ease of learning the graph inventory versus the ease of blending. Preliminary results show equivalent reading fluency rates of simple stories in the two writing systems, but deeper examination suggests that readers of the two systems may come to rely on different styles of reading. For example, Facefont (alphabetic) readers had a greater correlation between the number of graphs per word and the reading rate, which suggests a graph-by-graph reading strategy. Faceabary reading rate correlated more positively with the number of consonant clusters in a story, suggesting that readers gained in fluency due to the consolidation of phonological information within single graphs for complex consonant clusters (Hirshorn et al., 2012; Hirshorn et al., 2013).

Comparing the alphabetic and alphasyllabic systems also allowed us to examine the neural consequences of manipulating the grain size of O-P mapping. Neural differences have been observed in the laterality of the fusiform cortex response to printed English versus Chinese words, with English words eliciting a more left-lateralized response in a putative “visual word form area” (VWFA) (Nelson, Liu, Fiez, & Perfetti, 2009). Some have hypothesized that the differences are due to greater demand on spatial processing in Chinese. However, written English and Chinese vary in many dimensions, including the visual complexity and spatial layout of the graphs, and the grain size of O-P mapping. This makes it difficult to determine whether the observed laterality effects are due to perceptual factors or differences in the grain size of O-P mapping. Artificial orthographies provide a way to create scripts with similar visual-perceptual properties but different grain sizes of O-P mapping, thereby allowing the relative influence of these factors to be disentangled. To this end, we compared the neural activity in participants trained with Facefont vs. Faceabary while they passively viewed ‘face words’ in their respective scripts, and we found that Faceabary words (vs. patterns) elicited a more bilateral response in the fusiform cortex than Facefont words (Hirshorn et al., 2013). This suggests that the grain size used for mapping can influence the laterality of the neural substrates of reading.

As another way to test how the grain size of O-P mapping affects the involvement of the fusiform cortex in reading, we studied a patient (AA1) with an extensive lesion to her left inferior temporal cortex, including the typical territory of the VWFA (Moore et al., 2014). AA1 demonstrated the classic features of acquired alexia: a loss of automatic visual word recognition and reliance upon a letter-by-letter reading strategy. Prior work has shown that individuals with acquired alexia show chronic impairments in their ability to fluently read their native script. AA1 was taught a proto-alphabet (five phonemes at a time) and also a proto-syllabary, where units were one-syllable words (e.g., cap, may, be) or non-word syllables (e.g., duh). AA1 was only able to learn five phoneme-level visual graphs to criterion and was below average in using them to decode words (e.g., man). In contrast, she was able to reach ceiling (15 syllable-graphs) on the syllable/word artificial orthography and was able to use the learned graphs to decode words with precise O-P representations (may+ be= maybe) and imprecise O-P representations (cap + chin + duh = captioned). These results suggest that the ability to learn the O-P mappings for phoneme-level graphs, and to use the acquired knowledge to decode printed words, is particularly dependent upon the left fusiform cortex. On the other hand, neural territories outside of the left fusiform cortex may be sufficient to learn and use the graph inventories for scripts that use larger grain sizes for O-P mapping (Moore et al., 2014).

2.2 The Grain Size of Instruction and Its Impact on Reading

The grain size of instruction is the phonological unit that is the focus of attention for teaching, which has also been investigated as a source of learning differences (Ziegler & Goswami, 2005). A common aspect of the previous studies is that artificial orthographies with different sized mapping principles were also taught at a different grain size of instruction. However, it is possible to isolate the effect of the grain size of instruction by holding the grain size of the mapping principle constant. This issue is highly relevant for not only English, but for all writing systems where there is more than one viable option for instructional focus. There is no single universally accepted method for reading instruction across writing systems. Even within a writing system, substantial shifts in instructional theory and methods can occur over time, and instruction at a given point in time can vary across classrooms, schools, and geographic regions. Understanding how the grain size that is focused upon during instruction affects learning across writing systems could have significant influence on improving teaching methods.

Intuitively, the most appropriate unit of instruction for a given writing system would be the same as the grain size of the mapping principle. If that were true then alphabets should be taught at the phonemic level, alphasyllabaries and syllabaries at the syllabic level, and logographic systems at the whole word level. Consistent with this idea, a large body of research suggests that learners of alphabetic orthographies can achieve skilled reading through instruction that is largely based upon a phonemic approach that involves teaching letter-sound correspondences (Ziegler & Goswami, 2006). Despite this fairly straightforward approach, instruction for some alphabetic writing systems has historically started instruction with a focus on the syllable. This is the case in Spain, in which the ‘silabario’ plays a central role in beginning reading instruction (Durán, 2003). Instead of learning individual phonemes (e.g., /m/ and /a/), children start by learning CV syllables (e.g., /ma/, /me/, /mi/, /mo/, /mu/). This is one demonstration that the unit of instruction does not need to be the same as the grain size used within a writing system for O-P mapping.

Deeper, more phonologically inconsistent alphabets like English are thought to require additional instruction beyond the phonemic level (Goswami, Ziegler, Dalton, & Schneider, 2003). However, instruction for written English has been extremely variable throughout the last 150 years. Instruction used to begin with a focus on the syllable level, as reflected in the inclusion of a syllabary in the beginning pages of the *New England Primer* (The New-England Primer, 1789). Subsequent decades have seen various “reading wars,” which have involved debate about whether instruction should focus on phonemic, syllabic, or word-level units (Pearson, 2004). The previously described study by Asfaha et al. (2009), which involved comparisons between African language writing systems, once again provides a unique perspective on the role of grain size. In addition to examining mapping principle differences, this study examined variation in the grain size emphasized during instruction of an alphabetic script (Figure 4). The Saho teaching method, which emphasizes the syllable for instruction, was used in some geographic regions, while Kunama, which focuses on the phoneme level, was used in others. An advantage for syllable-level instruction in Grade 1 was observed, with a small but not significantly different advantage in Grade 4. This study again highlights the idea that the grain size of the writing system does not dictate the grain size of instruction. It also suggests that writing system instruction for languages with more complex syllabic structures does not necessarily need to focus on the phoneme-level. Conceptually related work with English was reported by Walton and colleagues (Walton & Walton, 2002; Walton, Walton, & Felton, 2001). They found that children trained to decode words using a rhyme analogy strategy (larger grain size of instruction) exhibited better reading outcomes, as compared to children trained to decode words using a letter-phoneme strategy (smaller gain size of instruction). Taken together, this work does not minimize the importance of phonemic coding, but rather highlights the potential utility of larger phonological units in reading instruction, as well.

Several research groups have used artificial orthographies to examine the effects of instructional grain size on single word learning, decoding, and their underlying neural substrates. These studies emerged in the context of debate about the relative merits of phonics versus whole-word approaches to reading instruction, and accordingly the experimental designs centered upon contrasting reading outcomes under phoneme-level versus word-level instructional conditions. For example, Bitan and colleagues examined the effect of instruction on transfer to reading novel words. They trained subjects on nonwords consisting of three letters, where each letter was made of two symbols (i.e. each word contained 6 components). The three groups varied in whether they: 1) received explicit phoneme-letter training, which paired the 2-symbol letters to Latin letters and their corresponding sounds (e.g., *| = ‘L’ = /l/), 2) were exposed to the words that had consistent sub-structure, but were not explicitly told about the structure, or 3) trained with stimuli with arbitrary mapping (Bitan & Booth, 2012). They found that improvement was only found in the explicit phoneme-letter instruction. Using a similar manipulation of instructional grain size, Bitan and colleagues also observed differences in the left posterior inferior frontal gyrus, which depended on whether participants were explicitly taught grapheme-phoneme rules or not (Bitan et al., 2005). The authors proposed that explicit instruction might lead to more automatic decoding, which in turn leads to reduced reliance on the left inferior frontal gyrus. These results suggest that being taught using a smaller instructional grain size leads to more generalizable and automatic reading processing. This type of research would have been nearly impossible using traditional cross-linguistic research methods, because individual letter knowledge is almost always learned before children learn to read. Thus, testing a ‘whole-word’ condition, without overt knowledge of the underlying letter-sound mapping, would be difficult. The authors also linked their results with a common distinction between memory systems subserving reading processes: procedural and declarative. They suggest that the letter-sound condition taps more into procedural memory processes, whereas the whole word condition taps into declarative memory processes. This could have implications for targeted instruction for individuals with either procedural or declarative system deficits (Ullman, 2001, 2004, 2005).

Other groups have utilized artificial orthographies to investigate how instructional grain size may contribute to observed differences in the laterality of neural processing across scripts. Yoncheva et al. (2010) used the N170, an ERP component known to show effects of orthographic word knowledge, to study the effects of instructional grain size on neural processing (Figure 4). Their artificial proto-orthography consisted of novel simple line drawings with different visual components that represented phonemes (8 consonants and 4 vowels), which were combined to create 32 CVC English words. Two groups of subjects were instructed to read visually identical novel words either using a phoneme or whole-word attentional focus. They found that subjects taught with a phoneme-level focus exhibited more of a left-lateralized N170 response compared to those taught with a whole-word focus. Complementary results were found using fMRI (Mei et al., 2012). In this study, words printed in an artificial orthography were similarly either taught with focus on the phoneme (as an alphabetic system) or whole word (as a logographic system). Their specific aim was to investigate laterality differences in the fusiform cortex, similar to the aim of the Faceabary project described above. Because the differences between laterality in English and Chinese reading has been attributed in differences in visual appearance, they kept visual appearance constant in order to study the effect of manipulating the instructional grain size. Interestingly, the laterality of the neural response in the fusiform cortex was modulated by the instructional grain size (more left-lateralized activation after alphabetic training than after logographic training). These results support the idea that the laterality difference between Chinese and alphabetic languages may have to do with grain size of mapping or instruction, rather than visual spatial processing, as previously hypothesized (Tan et al., 2001).

These studies are important especially because the left VWFA has been shown to be impaired in dyslexic readers (Shaywitz et al., 2004; van der Mark et al., 2009; van der Mark et al., 2011), and damage to this area leads to alexia (Beversdorf, Ratcliffe, Rhodes, &

Reeves, 1996; Damasio & Damasio, 1983). Knowing what specific dimensions of a writing system, such as grain size of the mapping principle or simply instructional focus, can influence the laterality of neural processing that supports skilled reading could be a powerful tool for helping those with reading deficits. If one has specific impairments in left hemisphere processing, being able to manipulate a writing system to rely relatively more on a bilateral reading network is an intriguing avenue to try to help to improve reading skill. Taken together, these studies that used artificial orthographies highlight how specific manipulations of instructional grain size can influence both learning and the neural substrates of reading.

2.3 The Grain Size of Internal Representations for Decoding

The third way to think about grain size emerges from consideration of phonological consistency within a writing system. Research suggests that differences in phonological consistency affect the size of the internal units or representations that are used for decoding, or the 'grain size of internal representations for decoding.' Each writing system has distinct statistical regularities of how phonology is mapped onto orthography at different levels of grain size that affect learning. Ziegler and Goswami (2005) posited that the efficiency with which a child can learn these statistical regularities, the stronger their internal lexical representations, and thus the more skilled their comprehension (Perfetti, 2007). Thus, using the appropriate or most efficient grain size of representation for a given language (or even word within an inconsistent language) could be thought to be at the core of what it means to be a skilled reader. Evidence for differences in the grain size of representation comes from cross-linguistic studies. For example, children learning to read English develop nonword reading strategies that involve analysis at the level of phonemes and rimes (e.g., final syllables that make words rhyme). In comparison, children learning to read German primarily use the phoneme level (Goswami et al., 2003; Ziegler et al., 2001). These differences have been attributed to relative differences in phonological consistency across the writing systems: German is more phonologically consistent at the phoneme-level, while English is more consistent at the rime level. Consequently, readers of English must focus on both phoneme and rime units during decoding (Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995; Ziegler & Goswami, 2006). Similarly, compared to English, Hebrew has a deep root structure such that there are consistent patterns of letters that are linked to meaning, which draws attention to larger units than just phonemes. This may explain why children who have learned to read Hebrew are better at deleting a relatively large unit (an initial syllable) from a spoken word than children who have learned to read English. The opposite pattern is observed when the task involves deleting an initial phoneme (Ben-Dror, Frost, & Bentin, 1995). While these studies have been informative, cross-linguistic research has not fully been able to explain what factors of experience or statistics may influence the development of the grain size of representations for decoding for a given writing system due to the lack of experimental control associated with this approach.

The artificial orthography methodology can provide insights where cross-linguistic comparisons may fall short. This is nicely demonstrated by Taylor, Plunkett, and Nation (2011) who used an artificial orthography approach to investigate how phonological consistency may impact the grain size of internal units of analysis. They systematically manipulated the spelling-sound consistency, frequency, and semantics of a set of 36 monosyllabic CVC nonwords printed using an alphabet of visually unfamiliar graphs, where the vowels varied in mapping consistency. Some vowels were always mapped onto a single sound, and others were pronounced differently depending on what consonant preceded them. Both consistent and inconsistent vowels occurred in high and low frequencies. A second variation of this task was repeated with half of the words paired with definitions. Post-tests were conducted to assess how consistency and frequency information affected generalization to novel words. The overarching goal was to see how subword regularities influence learning purely though exposure to whole word pronunciation. While vowel frequency, consistency, and access to semantics all affected learning, they found evidence that semantics affected learning to a greater extent at later stages of learning. These findings are informative for a language like English, where there is great variability in letter-sound consistency and frequency. As this study was only examining an alphabetic system, we cannot draw any conclusions about how grain size of the mapping principle or instruction affects the grain size of internal representations for decoding. Nevertheless, this approach could be especially useful in future work on alphasyllabaries. The grain size of instruction of alphasyllabaries varies between focus at the syllable or phoneme level, but little is known about what repercussions that has for internal representations used during reading. More generally, exploring how different dimensions of writing systems affect the grain size of representation for decoding has great potential for future work.

3. Applications for using Artificial Orthographies to Study Writing System Diversity

3.1 Theoretical Advancement

Some scholars propose that each writing system has evolved and settled on the most efficient combination of design features or dimensions for a given spoken language. As should be clear by now, typical cross-linguistic descriptive or even experimental comparisons are wrought with the covariance problem. Recent debates regarding whether or not writing systems are optimal or not (e.g., see Frost, 2012; Seidenberg, 2011) could benefit from using artificial orthographies. Do all languages get the writing system they deserve? Or are there improvements in learning that can be attained by isolating and manipulating one or more design principles? Artificial orthographies allow us to design experiments that question the optimality of the overall design of a writing system in a systematic manner.

3.2 Altering Old/Designing New Writing Systems

It may seem that the development of modern writing systems has ended, but in fact many orthographies continue to be modified both formally on a large scale, and on a smaller scale as is the case of short-hand or more informally as is seen in social media. In naturally occurring writing systems, some design parameters were chosen due to cultural or socio-historical reasons, which makes it difficult to determine the source of cross-linguistic differences in reading and writing. These have included colonization (e.g., in African languages; Bird, 1999), missionary work (e.g., Cree; Bennett & Berry, 1991), or sociopolitical reform (as in Korea during the Joseon Dynasty in 1443, or more recent reform to spelling norms in the Netherlands in 1995 and 2005 by the Dutch Language Union). Although these reforms have arguably mostly lead to gains in learning and reading fluency, there is a lack of a principled process for deciding how and why design elements are chosen in each circumstance. For example, as recently as 2005, the Dutch writing system has been modified in the Netherlands, with the spelling of some words adjusted. However, these modifications have been controversial and the pros and cons are for making such changes on reading and writing remain unclear. Such changes are almost surely part of a tradeoff between two competing design elements in a writing system (e.g., phonological consistency vs. semantic transparency), and artificial orthographies could aid in testing what the ramifications of modifying a writing system would be.

We also think of most writing systems as being extremely old, but that is not necessarily the case. Many Native American languages and African languages have been developed over the last 100-200 years and many languages, both spoken and signed, currently do not have a written form. However, there is not necessarily a principled method for testing whether new writing systems make sense for the natural language they are representing. For example, tonal languages in Africa (Bird, 1999) have a unique set of characteristics that may not be best represented by a Latin-based script. That is almost certainly the case for the natural signed languages of the world, none of which have a standardized or widely used written form. Signed languages tend to have rich morphological structure (Aronoff, Meir, & Sandler, 2005; Stokoe, 2005) conveyed through the visuospatial modality and a qualitatively different type of phonology (i.e., handshape, place), which continues to be an active area of research (Brentari, 2011; Liddell & Johnson, 1989). Artificial orthographies provide a tool to test the learning impact of design decisions before broad implementation, which is harder to correct.

3.3 Diagnosing and Treating Reading Disorders

Using artificial orthographies is a promising approach to achieve a more precise understanding of the dimensions of a writing system that both affect learning and lead to reading difficulties. A deeper understanding of how the dimensions of a writing system affect learning could lead to targeted diagnosis and treatment of reading disorders or deficits due to brain damage. It is possible that there are readers who have impaired phonemic representations that make learning an alphabet and decoding words difficult, but who have preserved syllable awareness (Wydell & Butterworth, 1999). For example, the fact that an acquired alexic patient with damage to the left inferior temporal cortex, presumably including the VWFA, was better able to learn a syllable-based artificial orthography than a phoneme-based one (Moore et al., 2014) suggests that the right-hemisphere is less affected by phoneme level deficits in reading. The fact that this behavioral pattern can be linked with a complementary neural signature is extremely informative. Interesting parallels could also be drawn to dyslexic readers, because they are naturally shown to have less left-lateralized reading networks (Maisog, Einbinder, Flowers, Turkeltaub, & Eden, 2008; Shaywitz et al., 2002).

If these patterns hold true, it could lead to using a “build on strengths” training approach that aims to leverage relatively preserved syllable-level phonological abilities to provide an alternative neural pathway to successful reading. Thus, the logic of using a syllable-based orthography would be to encourage the use of brain pathways that are more naturally engaged for dyslexic or alexic readers. The findings of Gleitman and Rozin (1973), who explored whether an artificial syllabary could serve as a remedial approach or transitional orthography for those learners that have difficulties with phonemic processing, provide support for this basic idea. More generally, artificial orthographies and studies manipulating the grain size of instruction could be a powerful tool to adjust teaching methods to help those with specific cognitive deficits. This could lead to being able to cater to the specific demands of the writing system and the individual differences among readers' capabilities.

In addition to factors such as phonological consistency and the different ways to study grain size, many other dimensions vary across writing systems. For instance, there are visual factors, such as the complexity of individual graphs and the extent to which visually similar letters also sound the same (e.g., 'm' and 'n' look and sound similar, 'b' and 'v' look different but are close in phonetic space, and 'o' and 'c' look similar but do not sound the same). Visual factors such as these may play a larger role in learning writing systems with a larger grain size of O-P mapping, because as the grain size of the mapping principle increases, the size of the total graph inventory will also increase. Consequently, visual processing demands may be a more significant hurdle to overcome on the path towards reading proficiency. Artificial orthographies could help to attain more targeted diagnoses or remediation (i.e., transitional orthography development) for a wide variety of deficits that impact reading skill.

3.4 Second Language Learning

Using cross-linguistic artificial orthographies could aid in understanding second language learning hurdles, especially given a specific native language. Research has shown that the cognitive and neural architecture of your L1 can affect how your reading your L2 (Tan et al., 2003). For example, Chinese-L1/English-L2 and English-L1/Chinese-L2 bilinguals were compared reading both English and Chinese, two languages that vary on many dimensions such as grain size/mapping principle, phonological consistency/semantic transparency, and visual complexity (Nelson et al., 2009). It was found that Chinese-L1/English-L2 engaged a similar network while reading English as Chinese, but English-L1/Chinese-L2 readers engaged additional areas while reading Chinese compared to English. This suggests that Chinese readers can use a 'Chinese' strategy and neural substrates for reading English, but English readers cannot use an 'English' strategy to read Chinese (Perfetti et al., 2007). This research highlights the idea that not only do the dimensions of a writing system itself affect the way you read a second language, but so too do the design principles of one's first language and how similar they are to their second language. Artificial orthographies could help in identifying which factors of an L2 are easy or difficult to master given a specific L1, and instruction could be adjusted accordingly.

4. Summary

In closing, despite great gains in understanding how writing systems affect learning to read through cross-linguistic comparison, we argue that artificial orthographies can provide a tool for further advancement. Considering the distinction and interaction between the grain size of the mapping principle, of instruction, and of internal representations for decoding can also help guide future research. Lastly, gaining a deeper understanding of the complex interactions between design principles and their influence on learning has important implications for theories of reading and writing systems, reading disorders, developing or revising writing systems, and second language learning.

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Highlights

- Writing systems have tradeoffs between visual and decoding demands
- Such tradeoffs could have greater effects on certain readers
- "Grain size" can mean: mapping principle, unit of instruction, unit for decoding
- Artificial orthographies help advance the study of writing systems and grain size

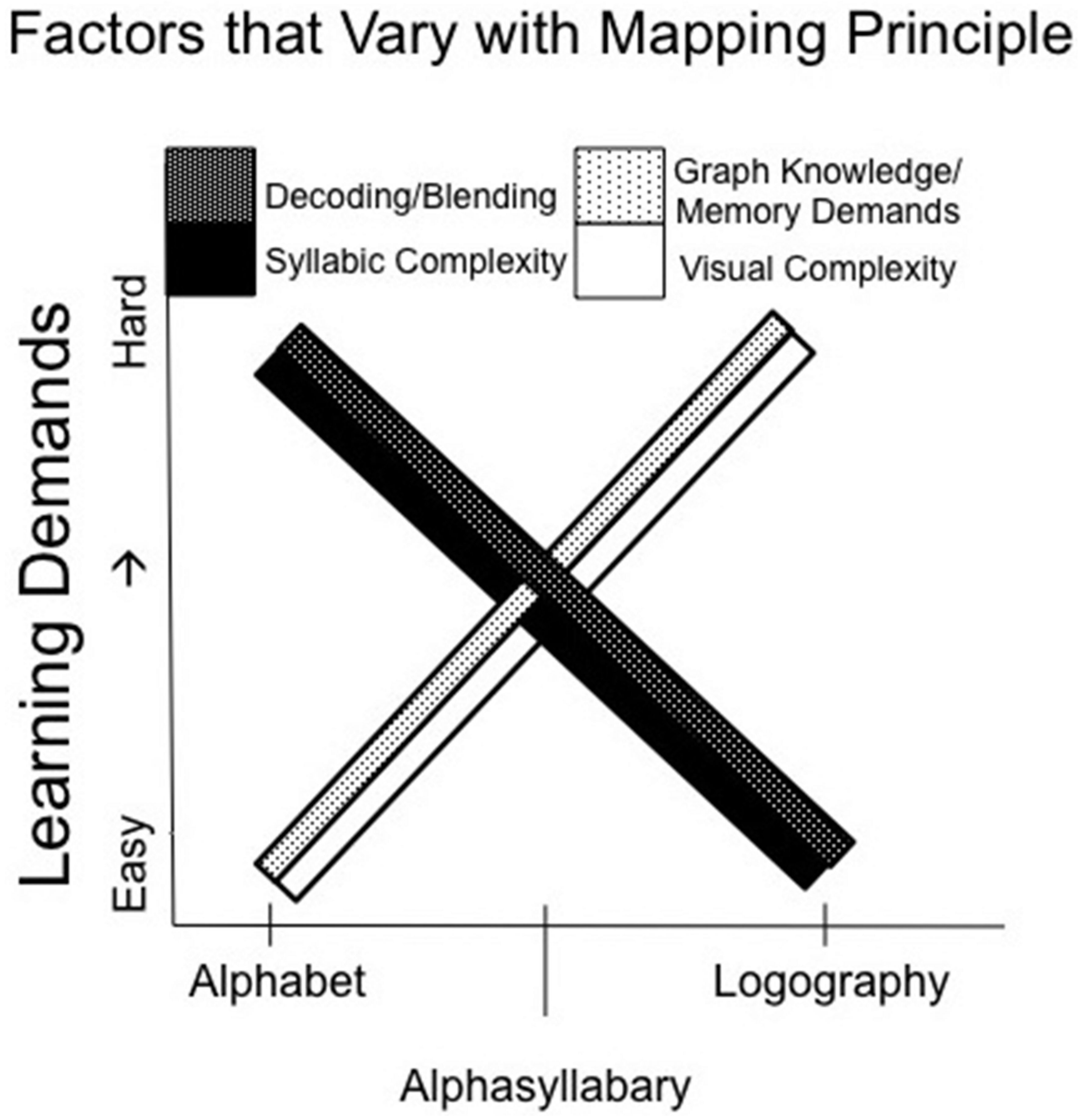

Figure 1.

Factors that Vary with Mapping Principle. An overarching trend is that phonological demands are greater in writing systems that use a small grain size for O-P mapping, whereas visual demands are greater in writing systems that use a large grain size for O-P mapping.

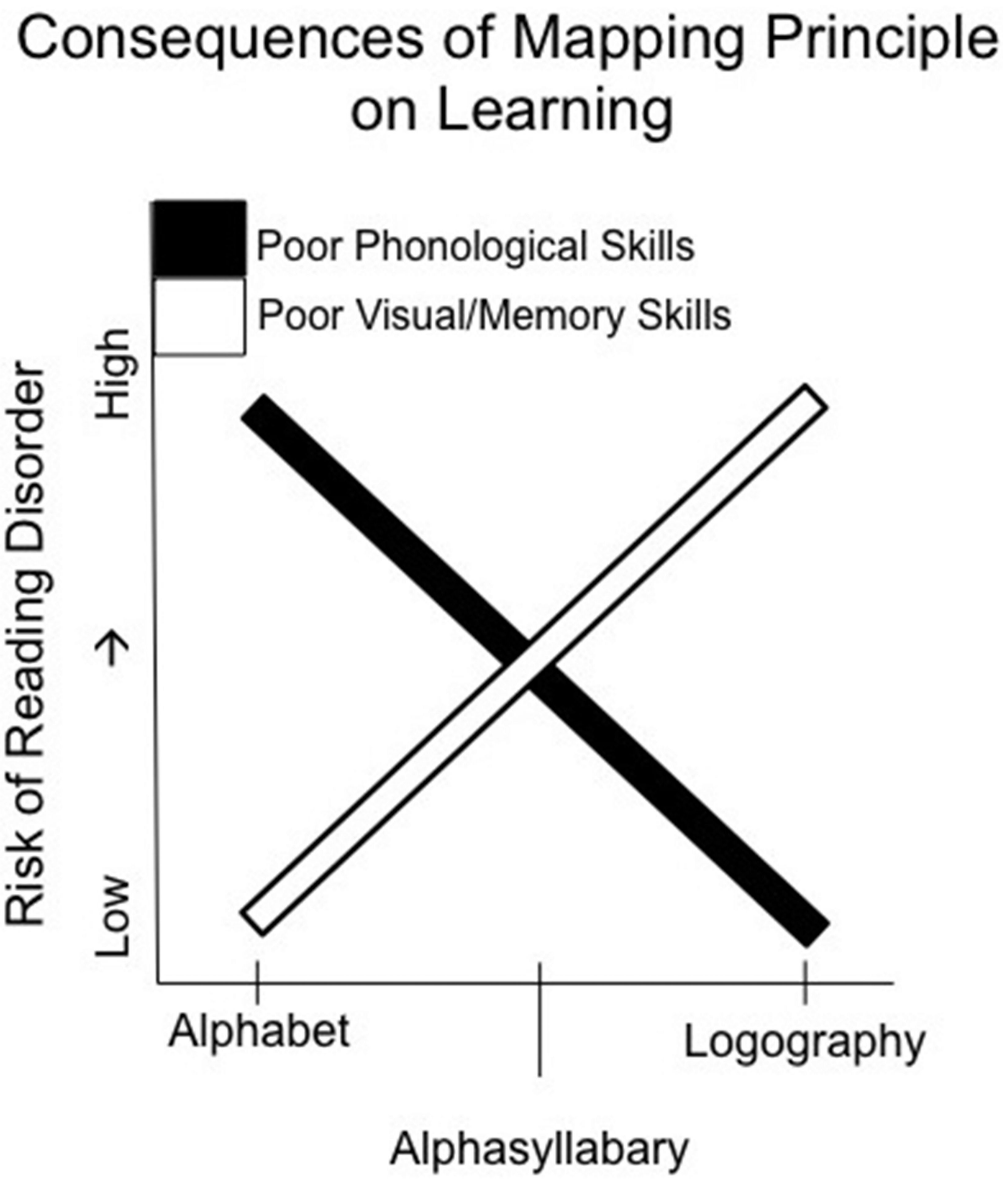

Figure 2.

Consequences of Mapping Principle on Learning. An overarching trend is that poor phonological skills lead to a greater risk of reading problems in writing systems that use a small grain size for O-P mapping, whereas poor visual/memory skills lead to a greater risk of reading problems in writing systems that use a large grain size for O-P mapping.

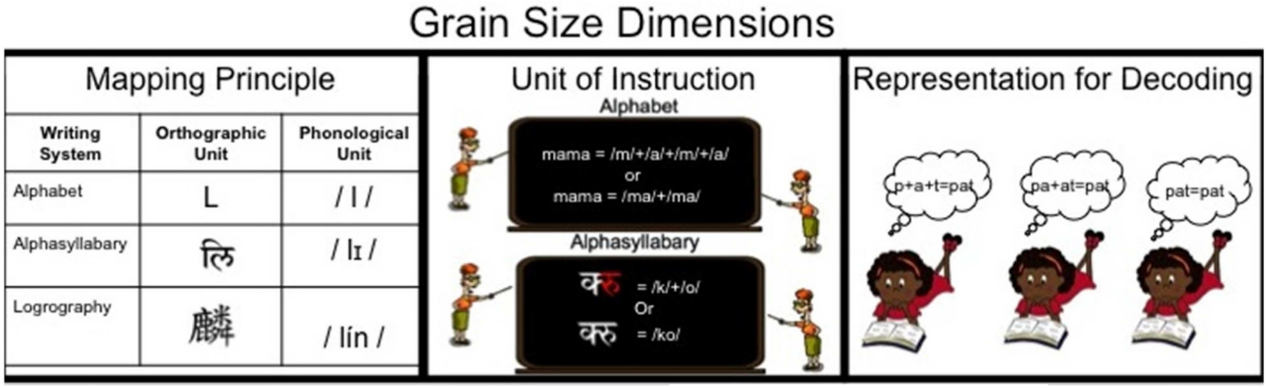

Figure 3.

Grain Size Dimensions. This figure illustrates three ways ‘grain size’ can be conceptualized. The mapping principle refers to the phonological unit that maps onto a single orthographic unit. The unit of instruction refers to the phonological unit that is the focus of attention in early stages of learning, which can be different than the mapping principle of a given writing system. The unit of representation for decoding refers to the phonological unit that is the building block for sounding out or decoding a word.

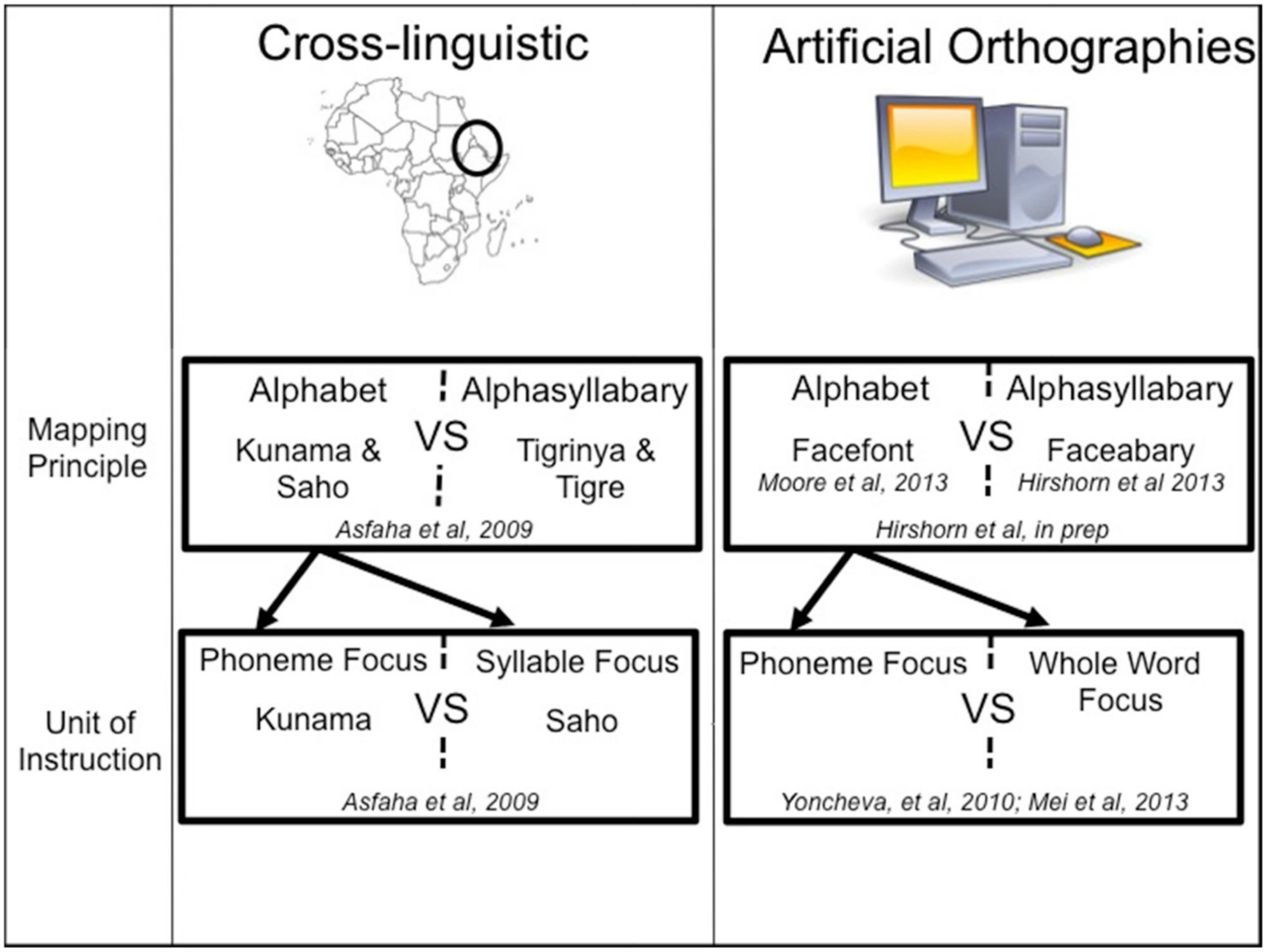

Figure 4.

Comparing Cross-linguistic and Artificial Orthography Methodologies for Studying Grain Size.

Table 1

Review of 13 published studies using artificial orthographies.

Addresses Topics Related to Grain Size							
	Authors	**Year**	**Mapping Princple**	**Instruction**	**Representation**	**Methodology**	**Specific Research Topic**
1	Sebesta	1964				behavioral	effect of O-P consistency on decoding
2	Gleitman & Rozin	1973	X			behavioral	decoding English with a syllabary
3	Bitan & Karni	2003		X	X	behavioral	letter decoding and word recognition
4	Bitan & Karni	2004		X	X	behavioral	letter decoding and word recognition
5	Bitan, Manor, Moroscz, & Karni	2005		X	X	fMRI	letter decoding and word recognition
6	Hart & Perfetti	2008				behavioral	lexical quality, phonological interfence
7	Maurer, Blau, Yoncheva, & McCandliss	2010				ERP	visual expertise
8	Yoncheva, Blau, Maurer, & McCandliss	2010		X		ERP	effect of instruction on N170 laterality
9	Taylor, Plunkett, & Nation	2011			X	behavioral	consistency, frequency, semantics and word reading
10	Bitan & Booth	2012		X	X	behavioral	letter decoding and word recognition
11	Mei et al.	2012		X		fMRI	effect of instruction on fusiform laterality
12	Moore, Durisko, Perfetti, & Fiez	2013				fMRI	fusiform laterality/visual vs phonological processsing
13	Moore, Brendel, & Fiez	2014	X			neuropsychology	alexia/learning in alphabet vs. syllabary