The substructure of phonics: The visual form of letters and their paradigmatic English
pronunciation are systematically related

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Abstract

We demonstrate, for the first time, significant systematicity between the visual form of letters of the Roman alphabet and their paradigmatic English pronunciation. We measure the visual distance between letters as Hausdorff distance and the phonological distance between their pronunciations as feature-edit distance. These two sets of distances are significantly positively correlated: letters that look the same tend to be pronounced the same. We discuss the implications for the teaching of the alphabetic principle in learning to read.

Keywords: systematicity, phonics, sound-letter mapping, font

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Language is characterized by systematicity within its subdomains—principally phonology, morphology, syntax and semantics. Researchers developed these subdomains theoretically precisely because there was clear structural systematicity involving the relevant abstractions of phonological features, phonemes, morphemes, syntactic categories, and semantic features. This systematicity is driven by informational requirements, but also reflects the robust redundancy necessary in the vulnerable medium of speech. Perception and cognition are increasingly seen in terms of ‘predictive processing’ (Clark, 2013); thus, active prediction drives language processing, compared with the traditional view of the listener/reader as passively accumulating data prior to parsing and interpretation. Maximizing any and all systematicity in speech maximizes predictability and ease of processing.

Researchers have increasingly identified systematic relations between the principal linguistic domains. For instance, there is a significant correlation between the phonological form of words and their meaning: words that sound the same tend to have similar meanings (Blasi, Wichmann, Hammarstrom, Stadler, & Christiansen, 2016; Monaghan, Shillcock, Christiansen, & Kirby, 2014; Shillcock, Kirby, McDonald, & Brew, 2001; Tamariz, 2008). This small but significant effect is separate from any similar effects of morphological and/or etymological relatedness and is more general than the effects of isolated pockets of phonetic symbolism (see below). Monaghan, et al. (2014) found that this correlation was largest in early-acquired words, suggesting systematicity is adaptive in early language learning. Tamariz (2008) found the same systematicity in Spanish words and reported that consonants contribute positively to this correlation, vowels negatively.

Phonological form has long been understood to have a relationship with meaning, as in phonetic symbolism (Hinton, Nichols, & Ohala, 2006; Newman, 1933; Sapir, 1929). For instance, the word-initial segments /sn/ are associated with nasal meanings, as in snore,

sneeze, snout, snot, sniff, snuff, etc. This systematicity may partly reflect such words having taken different historical routes into contemporary English, together with mutual priming keeping rarer words in usage. It may also reflect genuine iconicity operating through perceptuo-motor analogy (Dingemanse, Blasi, Lupyan, Christiansen & Monaghan, 2015).

Phonological form has a systematic relationship with syntactic category (Fitneva, Christiansen, & Monaghan, 2009; Kelly, 1992; Kelly, Morgan, and Demuth, 1996; Monaghan & Christiansen, 2008; Morgan & Demuth, 1996; Reali, Christiansen, & Monaghan, 2003). For instance, in English, nouns are more likely to contain a nasal segment, verbs a front vowel (Fitneva, et al., 2009). Shi, Morgan and Allopenna (1998) show that schwa is a reliable indicator of functor status across languages as different as English, Mandarin and Turkish.

Further generalizations across language structure have been observed. For instance, English adjectival ordering follows a ‘nouniness’ cline (Vendler, 1968) and there is a crosslinguistic preference for suffixing over prefixing (Cutler, Hawkins, & Gilligan, 1985).

These systematicities have emerged over the cultural history of the spoken language. Similar systematicities involving the written language have had a typically shorter timescale in which to emerge. Because of the nature of orthography, any such correlations have been observable by ordinary language-users and have even been subject to organized intervention, as with the creation of Korean orthography (Kim-Renaud, 1997), the simplification of traditional Chinese orthography (Chen, 1999), the emergence of ‘unpointed’ Hebrew (Frost, 1995), and the development of pinyin orthography for Standard Chinese (Chen, 1999). Scientific interest in reading has been overwhelmingly directed to alphabetic languages, notably English (cf. Share, 2008; Velan & Frost, 2011), and to the problem of the relation of its ‘deep’ orthography to its corresponding phonology (Harm & Seidenberg, 1999; Seidenberg & McClelland, 1989). Chinese orthography illustrates that a logographic orthography can have a direct relation between visual form and semantics: for instance, the graphical representation of ‘water’ is visible as the lefthand radical in the Chinese character

meaning ‘to take a bath’. It has been less obvious to researchers that English itself contains such direct visual relationships between orthography and meaning. For instance, the spelling of the phonological sequence /sai/ can be ‘psy-’ or ‘cy-’. These different spellings refer to different etymologies and to different meanings. This information would be lost if the spellings were regularized—a point consistently lost on generations of English would-be spelling-reformers. Similarly, /ʃʌn/ written as ‘tion’ as opposed to ‘shun’ indicates a morphological derivation.

In their large-scale study, Dautriche, Mahowald, Gibson, and Piantadosi (2017) demonstrated the crosslinguistic generality of the correlation between orthography and meaning; words that are spelled similarly tend to have similar meanings. This approach was intended to replicate the phonology-meaning systematicity, reviewed above, using orthographic form as an economical proxy for phonological form. However, it will surely have captured some aspect of the correlation between visual orthography and meaning discussed above.

Overall, language in all its forms is replete with adaptive systematicity. However, one potential correlation has been overlooked, it seems—the possible relationship between written letters and their sounds; for instance, the relationship between the visual form of the letter ‘a’ and its paradigmatic pronunciation /æ/, or between ‘c’ and /k/. For a native English speaker or a native Spanish speaker, the initial intuition is that this relation is as arbitrary as Saussure’s (1916) arbitrary nature of the linguistic sign. For a Korean speaker, the intuitive question is ‘has the cultural evolution of English orthography involved the (non-conscious) encoding of the sort of letter-sound systematicity that was consciously adopted by the creators of Korean orthography?’ For instance, is there a relationship that militates against the letters ‘m’ and ‘b’ referring equally well to the sounds /b/ and /m/ respectively, a relationship that favours their current use in written English and in teaching its alphabetic principle?

Below, we test the hypothesis that the relation between the visual form of English letters and their paradigmatic pronunciation is non-arbitrary.

Method

1. How to measure phonological distances

As a deep orthography (Frost, 2005; Seymour, Aro, & Erskine, 2003), English frequently connects more than one phoneme to a letter ('c' helps spell 'cite' and 'cat') and more than one letter to a phoneme (/k/ may be spelt as in 'cat' or 'kite'). Therefore, to measure phonological distance, we constrained the sound of a letter to the one used in the British phonics approach (Lloyd, Wernham, Jolly, & Stephen, 1998), which teaches the most frequent and common sound-letter relations; for example, 'a' is pronounced /æ/ as in 'cat' (see Table 1). We excluded 'x' and 'q' because the former is a polyphone /ks/, and the latter almost always co-occurs with 'u'. As a result, each of 24 letters was connected to only one phoneme. In the set of letters, there are $[(24 \times 24)/2 - 24]$, or 264, separate orthographic distances and 264 corresponding phonological distances.

Table 1.

One letter was associated with only one sound (examples from Lloyd, et al., 1998)

Letter	a	b	c	d	e	f	g	h	i	j	k	l
Phoneme	/æ/	/b/	/k/	/d/	/e/	/f/	/g/	/h/	/i/	/dʒ/	/k/	/l/
Example	ant	bat	cat	drum	egg	fish	gurgle	hop	ink	jam	cat	lollipop
Letter	m	n	o	p	r	s	t	u	v	w	y	z
Phoneme	/m/	/n/	/v/	/p/	/r/	/s/	/t/	/ʌ/	/v/	/w/	/j/	/z/
Example	meal	net	on	puff	rag	snake	tennis	umbrella	van	wind	yogurt	buzz

We chose the most detailed, comprehensive phonological specification available, to maximize the opportunities for a correlation to emerge¹. The phonemes were converted into feature-vectors taken from Harm and Seidenberg (1999), detailing manner and place of articulation (see Table 2). Values ranged from -1 to 1.

¹ Compare with, for instance, the less detailed specifications proposed by Shillcock, Lindsey, Levy, and Chater (1992) and Shipman and Zue (1982).

Table 2.

Phonological specification (Harm & Seidenberg, 1999) with British English examples (BE).

IPA	BE	H & S	Sonorant	Consonantal	Voice	Nasal	Degree	Labial	Palatal	Pharyngeal	Round	Tongue	Radical
/p/	puff	pat	-1	1	-1	-1	1	1	0	-1	1	0	0
/b/	bat	bat	-1	1	0	-1	1	1	0	-1	1	0	0
/t/	tennis	top	-1	1	-1	-1	1	-1	1	-1	-1	1	0
/d/	drum	dog	-1	1	0	-1	1	-1	1	-1	-1	1	0
/k/	cat	kite	-1	1	-1	-1	1	-1	-1	-1	-1	-1	0
/g/	gurgle	give	-1	1	0	-1	1	-1	-1	-1	-1	-1	0
/f/	fish	fit	-0.5	1	-1	-1	0	-1	1	-1	1	0	0
/v/	van	vine	-0.5	1	0	-1	0	-1	1	-1	1	0	0
/s/	snake	sit	-0.5	1	-1	-1	0	-1	1	-1	-1	1	0
/z/	buzz	jazz	-0.5	1	0	-1	0	-1	1	-1	-1	1	0
/h/	hop	hat	-0.5	1	0	-1	0	-1	-1	1	-1	-1	-1
/m/	meal	mop	0	0	1	1	1	1	0	-1	1	0	0
/n/	net	not	0	0	1	1	1	-1	1	-1	-1	1	0
/r/	rag	rat	0.5	0	1	0	-1	-1	-1	1	1	-1	-1
/i/	lollipop	loop	0.5	0	1	0	-1	-1	1	-1	-1	1	0
/w/	wind	win	0.8	0	1	0	0	1	-1	-1	1	-1	0
/j/	yogurt	yes	0.8	0	1	0	0	-1	0	-1	-1	0	1
/dʒ/	jam	gin	-0.8	1	0	-1	1	-1	0	-1	-1	0	0
/ɪ/	ink	hid	1	-1	1	0	0	-1	0	-1	-1	0	-1
/æ/	ant	hat	1	-1	1	0	-1	-1	0	1	-1	-1	1
/e/	egg	head (/ɛ/)	1	-1	1	0	-1	-1	0	-1	-1	-1	-1
/ɒ/	on	hot (/a/)	1	-1	1	0	-1	-1	-1	1	-1	-1	-1
/ʌ/	umbrella	hut	1	-1	1	0	-1	-1	-1	-1	-1	-1	-1

Table 2 represents phonemes as feature vectors. The distance between two phonemes is the distance between their vectors. Following Monaghan, et al. (2014), we measured this distance as a feature edit-distance².

² Euclidean distance between feature vectors was also investigated (results not reported here). It behaves similarly to feature edit-distance in correlations with orthographic metrics.

2. How to measure orthographical distances

We measured the distance between any two letter images as their Hausdorff distance (Huttenlocher, Klanderman & Rucklidge, 1993). Hausdorff distance compares two images in terms of their overlap³. Different fonts (Fig. 1) return different results for orthographic distance.

Fig. 1. Different fonts yield different orthographical distances.

We examined 23 representative English Microsoft fonts, categorized as san-serif, serif or cursive (Table 3). We saved the English alphabets as images at point-size 50 in Python 3.6, before measuring Hausdorff distances. We validated the use of Hausdorff distances by correlating them with the perceptual confusions reported by Geyer (1977). They were significantly correlated with both halves of the confusion matrix ($r = -.294, p < .000$; $r = -.143, p = .018$).

3. How to measure the correlation between phonological and orthographic distances

We took the set of visual distances between letters and the corresponding set of phonological distances between their pronunciations and measured their correlation for each font. We generated precise probabilities for the correlations using a Monte Carlo approach.

³ Compared with, for instance, the ‘perimetric complexity’ of Pelli, Burns, Farell and Moore-Page (2006), Hausdorff distance is sensitive to orientation, so that regular ‘l’ and italic ‘l’ yield a non-zero distance. Unlike perimetric complexity, Hausdorff distance is able to distinguish ‘p’ and ‘b’.

Table 3.
The 23 English fonts used.

Serif fonts	Sans-serif fonts	Handwriting style
	Arial	
	Candara	
	Calibri	
	Consolas	
Book Antiqua	Lucida Sans Unicode	<i>Lucida Handwriting</i>
Cambria	Microsoft Sans Serif	<i>Segoe Print</i>
Georgia	Segoe UI Symbol	<i>Segoe Script</i>
Palatino Linotype	Tahoma	
Times New Roman	Verdana	
Courier New	Franklin Gothic Medium	
Gabriola	Comic Sans MS	
	Arial Black	
	Impact	

Results

Distances between letter images tended to correlate significantly with the corresponding distances between how those letters are paradigmatically pronounced. Letters that look similar tend to be pronounced similarly. There was a range of correlations (Table 4), reflecting differences between the fonts. Serif fonts tended to give the highest correlations.

Monte-Carlo permutation testing (cf. Monaghan, et al., 2014) produced precise probabilities. The phonological distances were randomly paired 10,000 times with the orthographic distances and the correlation for each such trial was calculated, generating a distribution of correlations for each font. The position of the veridical correlation in the distribution was then recorded (Fig. 2).

Table 4.

Fonts ranked according to sound-letter correlation coefficients (Pearson's r)

Font	r	p-val	sig
<i>Gabriola</i>	0.290	0.000	***
<i>Georgia</i>	0.282	0.000	***
<i>Cambria</i>	0.267	0.000	***
<i>Times New Roman</i>	0.267	0.000	***
<i>Constantia</i>	0.262	0.000	***
<i>Book Antiqua</i>	0.241	0.000	***
Impact	0.231	0.000	***
<i>Palatino Linotype</i>	0.227	0.000	***
<i>Calibri</i>	0.222	0.000	***
Franklin Gothic Medium	0.216	0.000	***
<i>Lucida Sans Unicode</i>	0.212	0.000	***
<i>Consolas</i>	0.211	0.000	***
<i>Tahoma</i>	0.210	0.000	***
Comic Sans MS	0.206	0.001	***
<i>Candara</i>	0.204	0.001	***
<i>Segoe UI Symbol</i>	0.198	0.001	***
<i>Segoe Script</i>	0.185	0.002	**
<i>Verdana</i>	0.178	0.003	**
<i>Arial</i>	0.167	0.005	**
Segoe Print	0.163	0.007	**
<i>Microsoft Sans Serif</i>	0.161	0.008	**
<i>Courier New</i>	0.115	0.056	.
<i>Lucida Handwriting</i>	0.108	0.074	.
Arial Black	0.102	0.091	.

Note: * < .05, ** p < .01, *** p < .001, Orthographical distance M=4.12, SD=0.68, Phonological distance M= 5.22, SD=1.72, Dark grey: serif, Light grey: handwriting, White: sans-serif.

(a) Serif fonts

(b) Sans-serif fonts

(c) Handwriting style fonts

Fig. 2. Results of the Monte-Carlo permutation test. Boxes show the first to third quartile; lines within boxes show the median; bars show the range of randomized mappings; filled circles show veridical correlations.

We further investigated the contribution of each letter to the overall correlation of its font. Table 5 shows the correlation re-calculated without each letter, for the representative Georgia font. As in the other fonts, the letter ‘m’ tended to make the largest contribution. As in Monaghan et al.’s (2014) and Tamariz’s (2008) studies of the lexicon, we are not exclusively concerned with positive correlations. The systematicity exists despite elements that contribute towards a negative correlation. The overall correlation for Georgia was $r = .282$. In Georgia, as in the other fonts, the letters ‘r’, ‘y’, ‘v’, ‘b’ and ‘d’ tended to disrupt the systematicity whereas ‘m’, ‘w’, ‘t’ and ‘c’ were likely to be the leading contributors towards it.

Table 5.

The correlation without each letter in turn, for Georgia font (overall $r = .282$).

	r	p-val
y	0.317	0.000
k	0.312	0.000
d	0.312	0.000
i	0.309	0.000
l	0.304	0.000
v	0.304	0.000
r	0.301	0.000
p	0.299	0.000
b	0.295	0.000
f	0.291	0.000
e	0.286	0.000
j	0.282	0.000
n	0.281	0.000
o	0.279	0.000
c	0.276	0.000
a	0.273	0.000
h	0.271	0.000
s	0.271	0.000
u	0.270	0.000
w	0.269	0.000
t	0.268	0.000
z	0.268	0.000
g	0.264	0.000
m	0.118	0.062

Note: Without ‘y’ the correlation coefficient increases, without ‘m’ it decreases and without ‘j’ it stays the same at .282.

Discussion

We have added to the growing catalogue of instances of systematicity in language use. In this case, the systematicity involves the simplest level of written letters: the letters of the English alphabet have a non-arbitrary relationship with their paradigmatic pronunciations—the more visually similar the letters the more phonologically similar their pronunciations. This first demonstration of systematicity between the letters of the Roman alphabet and spoken English parallels the other examples of adaptive systematicity reviewed above. It also parallels, on a smaller scale, the consciously developed systematicity of Korean

orthography. Considered alone, the effect is relatively small but a systematicity accounting for even some 5% of the variance may facilitate early learning and later processing. The other systematicities reviewed above are typically smaller than the one we report. It is the cumulative effect of all these necessarily rather small systematicities that is critical.

The size of the correlation varies across fonts, but there is a secure significant effect, generated by the basic shape of the letters and by orthographic features such as serifs that accentuate the basic form of letters. Many changes have happened over the history of English orthography—changes in access to literacy, in the phonology of English, in contact with other languages, in the English lexicon, in the technology of printing. These changes are all opportunities for small changes to have been made and reinforced by readers' and writers' susceptibility to systematicity in learning and in language use.

What is the psychological nature of visual and phonological complexity? We have measured each type of complexity to reflect current research, one criterion being that the metrics should be sufficiently detailed to allow a correlation to emerge. However, there may be psychologically more relevant versions of each metric. Hausdorff distance has its origins in mathematics. One advantage was that it is sensitive to orientation. However, the psychology of visual processing—the nature of eye-movements in reading, the visual pathways from retina to cortex, and the details of cortical visual processing—may suggest metrics that reveal greater systematicity. The measure of phonological distance we employed, based on manner and place of articulation, has its origins in mainstream phonological theory, oriented towards speech *production*. It may be that speech *perception* should play a role in a measure of phonological distance. It may be that we should take account of the order of acquisition of the phonemes in infancy (itself a measure reflecting perception, production, the English lexicon and culture) (cf. Grunwell, 1981; Smit, Hand, Freilinger, Bernthal, & Bird, 1991). The correlation we report is a first step in exploring the psychological dimensions of this aspect of systematicity in language.

A critical next step is to understand the role of those letter-sound correspondences that tend to disrupt the positive correlation we report. A positive correlation is only one aspect of systematicity. Disruptive correspondences and negative correlations can complement our understanding of the contribution of positive correlations to systematicity and its relationship with overriding informational requirements. Similarly, we need to understand the learning implications of the skewed contributions of the individual letters, as seen in Table 5.

Finally, we can change fonts to increase the size of the correlation. Although orthography is just as much an artefact—a ‘cognitive tool’—as the spoken language, it is much more labile: designers create new fonts, individuals choose favourite fonts, specific fonts are used for different purposes. Psychologists have explored how features of fonts, such as serifs, affect legibility, reading speed and information recall (Arditi & Cho, 2005; Gasser, Boeke, Haffernan & Tan, 2005) particularly in the early stages of learning to read (Sheedy, Subbaram, Zimmerman, & Hayes, 2005) and in dyslexia (French, et al., 2013; Rello & Baeza-Yates, 2013). The correlation we report shows that we can quantify the comparison of different fonts in a principled way when looking for effects of font on: (a) beginning readers who are learning the alphabetic principle—perhaps there is an optimal order in which the letters should be learned in a phonics approach, perhaps there is an optimal font; (b) dyslexic reading—perhaps facilitating the generation of the phonological form of words will benefit dyslexics; (c) skilled adult reading—perhaps the same facilitation of phonological form can assist skilled fluent reading; (d) changes to fonts (e.g. simplifications) prompted by reading/writing technology or education initiatives. In all of these cases, we now have a principled, quantitative approach to font design that can be used to maximize the correlation with phonological form while staying acceptably close to recognized fonts.

Conclusion

We report for the first time significant systematicity in the relationship between letters and their corresponding paradigmatic pronunciation in the Roman alphabet: letters that look

similar tend to sound similar. This systematicity reflects the cultural history of the Roman alphabet in English text. We suggest that this systematicity is adaptive in reading and in learning to read. It may be exploited in the phonics approach to teaching reading. In a sense, the correlation we report represents ‘the substructure of phonics’.

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