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Letter Features as Predictors of Letter-Name Acquisition in Four Languages with Three Scripts

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ABSTRACT

To expand our understanding of script-general and script-specific principles in the learning of letter names, we examined how three characteristics of alphabet letters – their frequency in printed materials, order in the alphabet, and visual similarity to other letters – relate to children's letter-name knowledge in four languages with three distinct scripts (English [$N = 318$; M age = 4.90], Portuguese [$N = 366$; M age = 5.80], Korean [$N = 168$; M age = 5.48], and Hebrew [$N = 645$; M age = 5.42]). Explanatory item response modeling analysis showed that the frequency of letters in printed materials was consistently related to letter difficulty across the four languages. There were also moderation effects for letter difficulty in English and Korean, and for discriminatory power of letters in Korean. The results suggest that exposure to letters as measured by letter frequency is a language-general mechanism in the learning of alphabet letters.

In languages with alphabetic writing systems, children often learn the names of the letters early in the course of literacy acquisition. Letter-name knowledge is strongly associated with early literacy skills, including word reading and spelling, in languages as diverse as English (see Adams, 1990; National Early Literacy Panel, 2008; National Research Council, 1998, for review), Brazilian Portuguese (Cardoso-Martins, Resende, & Rodrigues, 2002), Korean (Kim, 2011), Hebrew (Levin & Aram, 2004; Shatil, Share, & Levin, 2000), Turkish (Oney & Durgunoglu, 1997), and Latvian (Sprugevica & Hoien, 2003). Letter-name acquisition is influenced by characteristics of children (e.g., phonological memory, phonological awareness; de Jong & Olson, 2004; Diamond, Gerde, & Powell, 2008; Torppa, Poikkeus, Laakso, Eklund, & Lyytinen, 2006) and – of particular interest here – by characteristics of letters (e.g., frequency in printed materials, visual similarity, order in the alphabet; Kim & Petscher, 2013; Levin, Patel, Margalit, & Barad, 2002; Treiman, Levin, & Kessler, 2007).

Although the previous studies are informative, we still have a limited understanding of which characteristics of letter-name learning hold across scripts and which are specific to particular scripts. In order to fill this gap, we studied four languages with three distinct scripts – English, Portuguese, Korean, and Hebrew – reanalyzing data from children who had not yet received systematic instruction about alphabet letters (English and Portuguese data from Treiman, Kessler, & Pollo, 2006, Korean data from; Kim & Petscher, 2013, and Hebrew data from Treiman, Levin, et al. [2007]). We investigated how three features of letters – frequency in printed materials, order in the alphabet, and visual similarity – are related to children's letter-name knowledge. We examined the relations of these features not only to the difficulty of letters but also to their discriminatory power, that is, the extent to which they distinguish children with varying levels of letter knowledge.

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Learning letter names involves associating shapes to labels. Because the associations between letter shapes and names are generally arbitrary, frequency of exposure to letters is likely to be an important mechanism in letter-name learning. The importance of exposure frequency in learning, particularly in learning of arbitrary associations such as those between words and objects, has been consistently noted (Hart & Risley, 1995; Schwartz & Terrell, 1983; Woodward, Markman, & Fitzsimmons, 1994; Yu, 2008). Thus, it is reasonable to expect that exposure frequency would influence letter-name learning across scripts. One source of exposure is printed materials, including books and other print in the environment (Huang & Invernizzi, 2012; Treiman et al., 2006; Turnbull, Bowles, Skibbe, Justice, & Wiggins, 2010). Letters that occur more frequently in printed materials might receive greater attention by children, as parents and teachers interact with children using printed materials, and this may facilitate storage of these letters' names in memory (Robins, Treiman, & Rosales, 2014). Evidence on the role of letter frequency, however, is mixed. Letter frequency in printed materials explained U.S. kindergartners' knowledge of lowercase letters after accounting for several other features of letters, including visual similarity and inclusion in the child's own name (Huang & Invernizzi, 2012). Similar findings were reported for U.S. prekindergartners (Turnbull et al., 2010) and for Israeli prekindergartners and kindergartners (Treiman, Levin, et al., 2007). However, other studies found that letter frequency was not related to letter knowledge in English (Evans, Bell, Shaw, Moretti, & Page, 2006) or Korean (Kim & Petscher, 2013) or the extent to which children confused pairs of letters in Portuguese (Treiman et al., 2006).

Another letter feature that may be relevant to letter-name acquisition is the position of the letter in the alphabet. Letters that are at or near the beginning of the alphabet string are likely to receive greater attention in informal learning contexts (e.g., games, television shows) and formal letter contexts (e.g., educational programs that present letters starting with the first letter of the alphabet and proceeding to the last). Indeed, studies have shown that U.S. children are more likely to know the names of letters that are early in the alphabet sequence (i.e., A, B, & C) than expected on the basis of other factors (Justice, Pence, Bowles, & Wiggins, 2006; McBride-Chang, 1999) and that U.S. parents and children are more likely to discuss these letters (Robins et al., 2014). However, the effect of letter order was limited in Korean (Kim & Petscher, 2013).

A third potential source of variability among letters is the visual similarity of a letter to others. Greater visual similarity among letters can make distinguishing them more difficult and is related to errors in naming letters in English (Blair & Ryckman, 1969; Bowles, Pentimonti, Gerde, & Montroy, 2014; Cohn & Stricker, 1979; Treiman & Kessler, 2003; Treiman et al., 2006), Hebrew (Treiman, Levin et al., 2007), Arabic (Levin, Saiegh-Haddad, Hende, & Ziv, 2008), and Portuguese (Treiman et al., 2006). For instance, English- and Portuguese-speaking children were more likely to confuse the names of letters that are visually similar (e.g., W and V) than of those that are less similar (Treiman et al., 2006). However, a study with Korean children found that visual similarity was not independently related to letter-name knowledge after controlling for child characteristics such as phonological awareness and other letter characteristics such as letter order (Kim & Petscher, 2013).

What is clear in this brief review are the inconsistencies in the previous results across scripts and studies. What is not clear is whether the divergent results are due to characteristics of scripts or characteristics of studies. Because studies differed in the outcomes and predictors as well as the scripts, the results cannot be directly compared. For instance, the outcome in the studies of Blair and Ryckman (1969), Cohn and Stricker (1979), and Treiman et al. (2006) was whether children confused pairs of letters. In other studies, the outcome was whether children correctly produced letters' names. Studies also differed in the predictors that were included in the statistical models and how variables were defined. For example, visual similarity was operationalized as "the number of other letters whose visual forms share 50% or more of strokes in target letter's form" (Treiman & Kessler, 2003, p. 271) in some studies (Kim & Petscher, 2013; Treiman & Kessler, 2003), on the basis of adults' ratings of the similarity of letters in other studies (Treiman et al., 2006, p. 2007), and categorically in still other studies (e.g., "not often confused" such as *o, r, x*; "sometimes confused" such as *a, c, e*; "often confused" such as *i, j, k*; "very often confused" such as *b, d, g*; Huang &

Invernizzi, 2012). These differences make it difficult to identify factors that are consistent contributors across languages and scripts versus factors that are specific to certain languages or scripts. In the present study, we included the same predictors in the statistical models for each language that we studied, and we operationalized them in the same way.

Letter characteristics of English, Portuguese, Korean, and Hebrew

Table 1 provides information about the letters in each of the languages that we studied. Although English and Portuguese both use letters of the Latin alphabet, the names and the relative frequencies of the letters differ between the two languages. For instance, V appears in print much more frequently in Portuguese than in English. Another difference between English and Portuguese is that K, W, and Y are rarely used in Portuguese, appearing only in foreign words and proper names. Therefore, 26 letters and 23 letters were used in the letter name assessments in English and Portuguese, respectively. The Korean alphabet has a total of 40 letters. The first 14 letters in Table 1 represent consonants and have names that begin with consonants. They were designed after the shapes of articulatory organs when producing the letters' sounds. For example, ㄱ, which represents/k/, depicts the shape of the tongue when articulating the sound. The next set of 10 Korean letters in Table 1 are vowels whose names match the sound they represent. These vowel letters were created using the basic shapes · (which later became a short stroke), ㅡ, and ㅣ, which, respectively, represent sky, earth, and a human– three basic elements of the universe according to an ancient philosophy. Vowel letters differ in whether short strokes are on the left (e.g., ㅓ), right (e.g., ㅏ), top (e.g., ㅗ), or bottom (e.g., ㅜ) of the basic strokes. This means that vowel letters are generally more visually similar to other vowel letters than are consonant letters. Next in Table 1 are the double consonant letters, which may be identified because their names begin with/ssaŋ/. The last 11 letters are double vowel letters that are constructed by combining basic vowels (e.g., ㅐ is a combination of ㅏ and ㅣ), meaning that their visual similarity to other vowel letters is particularly high. Double vowel letters also tend to occur less frequently than other letters. The Hebrew alphabet (see Table 1) has 22 letters, 5 of which have a different shape when they occur at the end of a word than when they appear in other positions. These final forms were not tested in the data sets used in the present study. In English and Portuguese, uppercase letters were used in the assessment. Korean and Hebrew have only one case.

Present study

The present study was designed to expand our understanding of script-general and script-specific principles in the learning of letter names by examining data from learners of English, Portuguese, Korean, and Hebrew. By analyzing data from these four languages and three scripts, we can examine whether effects of letter frequency, letter order, and visual similarity are similar or different across scripts.

We also extend previous studies by examining the relations of letter frequency, letter order, and visual similarity to two outcomes: difficulty and discrimination. The vast majority of previous studies examined the letter features that help to explain which letters are easier and which are more difficult. With the exception of a few studies, such as Phillips, Piasta, Anthony, Lonigan, and Francis (2012) and Bowles et al. (2014), previous studies did not examine discrimination – how well the letter (item) distinguishes individuals who know letter names from individuals who do not. It is important to investigate letter discrimination because it can inform selection of letters in assessments of letter-name knowledge. Given the strong predictive power of students' letter-name knowledge for early reading and writing skills, letter knowledge is frequently tested in early grades. In such a context, it can be useful to test a smaller set of letters with high discrimination values rather than all letters (Petscher & Kim, 2011; Phillips et al., 2012). We further extended prior work by examining potential moderation effects of letter features on both letter difficulty and letter discrimination. For instance, the effect of

Table 1. Letters tested in each language with international phonetic alphabet form and proportion correct on each letter.

American English (*N* = 318)		Brazilian Portuguese (*N* = 366)		Korean (*N* = 168)		Hebrew (*N* = 645)	
Letter	Proportion Correct	Letter	Proportion Correct	Letter	Proportion Correct	Letter	Proportion Correct
A/e/	0.97	A/a/	0.90	/kɪjʌk/	0.85	א/'alɛf/	0.87
B/bi/	0.96	B/be/	0.75	ㄴ/nɪɯɨn/	0.70	ב/bet/	0.73
C/si/	0.94	C/se/	0.69	ㄷ/tɪkɯt/	0.86	/'gimel/	0.63
D/di/	0.90	D/de/	0.53	ㄹ/lɪɯl/	0.89	ד/'dalɛd/	0.53
E/i/	0.90	E/ɛ/	0.71	ㅁ/mɪɯm/	0.73	ה/hei/	0.52
F/ɛf/	0.87	F/'ɛfi/	0.65	ㅂ/pɪɯp/	0.90	ו/vav/	0.43
G/dʒi/	0.84	G/ʒe/	0.70	ㅅ/ʃɪot/	0.90	ז/'zajin/	0.41
H/etʃ/	0.88	H/a'ga/	0.69	ㅇ/ɪɯŋ/	0.89	ח/xet/	0.46
I/ɑɪ/	0.88	I/i/	0.76	ㅈ/cɪɯt/	0.92	ט/tet/	0.40
J/dʒe/	0.88	J/'ʒɔta/	0.71	ㅊ/tʃɪɯt/	0.66	י/jod/	0.75
K/ke/	0.90	L/'ɛli/	0.71	ㅋ/kʰɪɯk/	0.79	כ/kaf/	0.40
L/ɛl/	0.92	M/'emi/	0.72	ㅌ/tʰɪɯt/	0.81	ל/'lamɛd/	0.56
M/ɛm/	0.90	N/'eni/	0.65	ㅍ/pʰɪɯp/	0.30	מ/mem/	0.53
N/ɛn/	0.88	O/ɔ/	0.80	ㅎ/hɪɯt/	0.58	נ/nun/	0.45
O/o/	0.99	P/pe/	0.74	ㅏ/a/	0.90	ס/'samɛx/	0.52
P/pi/	0.92	Q/ke/	0.45	ㅑ/ja/	0.76	ע/'ajin/	0.57
Q/kju/	0.83	R/'ɛhi/	0.75	ㅓ/ʌ/	0.72	פ/pei/	0.48
R/ɑr/	0.92	S/'ɛsi/	0.65	ㅕ/jʌ/	0.81	צ/'tsadik/	0.44
S/ɛs/	0.93	T/te/	0.64	ㅗ/o/	0.68	ק/kuf/	0.44
T/ti/	0.88	U/u/	0.76	ㅛ/jo/	0.82	ר/reʃ/	0.54
U/ju/	0.83	V/ve/	0.58	ㅜ/u/	0.81	ש/ʃin/	0.69
V/vi/	0.73	X/ʃis/	0.88	ㅠ/ju/	0.73	ת/taf/	0.56
W/'dʌbəlju/	0.87	Z/ze/	0.53	ㅡ/ɯ/	0.68	-	-
X/ɛks/	0.96	-	-	ㅣ/ɪ/	0.84	-	-
Y/wɑɪ/	0.84	-	-	ㄲ/ssaŋkɪjʌk/	0.76	-	-
Z/zɪ/	0.92	-	-	ㄸ/ssaŋtɪkɯt/	0.62	-	-
-	-	-	-	ㅃ/ssaŋpɪɯp/	0.53	-	-
-	-	-	-	ㅆ/ssaŋsɪɯt/	0.85	-	-
-	-	-	-	ㅉ/ssaŋcɪɯt/	0.70	-	-
-	-	-	-	ㅐ/ɛ/	0.70	-	-
-	-	-	-	ㅒ/jɛ/	0.61	-	-
-	-	-	-	ㅔ/ɛ/	0.81	-	-
-	-	-	-	ㅖ/jɛ/	0.61	-	-
-	-	-	-	ㅘ/wa/	0.77	-	-
-	-	-	-	ㅙ/wɛ/	0.81	-	-
-	-	-	-	ㅚ/wɛ/	0.86	-	-
-	-	-	-	ㅝ/wʌ/	0.80	-	-
-	-	-	-	ㅞ/wɛ/	0.60	-	-
-	-	-	-	ㅟ/wɪ/	0.52	-	-
-	-	-	-	ㅢ/ɯɪ/	0.70	-	-
M	0.89	-	0.69	-	0.74	-	0.54
SD	0.05	-	0.10	-	0.13	-	0.13

visual similarity may depend on letter order or frequency, and this may differ depending on languages and/or scripts.

The specific research questions that guided the present study were thus as follows: (1) What are the roles of letter frequency in printed materials, letter order, and visual similarity in children's letter-name knowledge in terms of difficulty and discrimination in English, Portuguese, Korean, and Hebrew? (2) Do the roles of these features in difficulty and discrimination vary as a function of each other? We hypothesized that the letter features would relate to letter difficulty but, given the mixed results of previous studies, we did not have clear hypotheses about their unique independent relation after controlling for the other features and about their relations to discriminatory power.

Method

Participants

Data in the present study include English and Portuguese data from Treiman et al. (2006; three children in this study were not included due to missing age information), Korean data from Kim and Petscher (2013), and Hebrew data from Treiman, Levin, et al. (2007).[1] Table 2 provides information about the number of children in each study and about the children's ages and genders. The studies of English, Portuguese, and Hebrew were originally designed to examine the relations of child factors and letter features to letter-name knowledge and naming errors. The study of Korean examined the relations of child and letter features to letter-name and letter-sound knowledge. English-speaking participants were from Detroit, Michigan; Portuguese-speaking participants were from Belo Horizonte, Brazil, and mostly from private schools; Korean participants were from a private institute in South Korea; and Hebrew-speaking participants were from public and private institutes in Israel. The US and Brazilian children were primarily from middle-class families, the Korean children were from families of low-average and average socio-economic status, and the Hebrew-speaking children had a range of backgrounds. At the time the data were collected, letter shapes and names were informally taught to children of the ages tested here in all four language contexts. Formal teaching about letters and reading was not a part of the curriculum.

Measures

Letter-name knowledge was the outcome measure, and the predictors included letter frequency, letter order, and visual similarity.

Letter-name knowledge

In English and Portuguese, children were shown one letter at a time on a card and asked to name it (Treiman et al., 2006). In the study with Hebrew children, simple drawings were interspersed with the letters and children were asked to name the drawings and letters (Treiman, Levin, et al., 2007). In Korean, four rows of three letters each were presented on pages, and the child was asked to name the letter to which the assessor pointed (Kim & Petscher, 2013). In each study, all of the letters were presented in a single session, and testing took place in a quiet area.

Letter frequency in printed materials

For English, we used the frequency of each letter in written materials at the kindergarten and first-grade levels according to the corpus of words from Zeno, Ivenz, Millard, and Duvvuri (1995). A similar approach was adopted in Portuguese (see Treiman et al., 2006, for further information), using the preschool and first-grade corpus of Pinheiro (1996) and ignoring the presence of diacritic marks on letters (e.g., á for an accented vowel). For Korean, frequency of letters was based on first-grade reading textbooks (see Kim & Petscher, 2013). In Hebrew, the letter frequency information was based on 137 books designed for toddlers through kindergartners (see Treiman, Levin, et al., 2007).

Letter order

We coded letter order based on the sequence in which letters are typically discussed in each language, which is shown in Table 1. This corresponds to the order in the dictionary in English, Portuguese, and

Table 2. Sample size, age, and percent girls in the four data sets.

Language	N	Age (mean, range)	Percent girls
English	318	4.90 (3.80–5.90)	50
Portuguese	366	5.80 (3.25–6.75)	53
Korean	168	5.48 (4.25–8.00)	46
Hebrew	645	5.42 (3.93–6.11)	47

Hebrew. In Korean, the order in which letters are discussed by the public is different from that adopted in dictionaries (see the Korean Ministry of Education, 1988 and the National Institute of Korean Language, 2020).[2] We coded for the former because we expected that it would be more likely to influence children's learning.

Visual similarity

For the Latin script (i.e., English and Portuguese), 30 US college students were shown pairs of letters and were asked to rate their visual similarity on a scale of 1 (*not at all similar*) to 7 (*very similar*; see Treiman et al., 2006, for details; see Simpson, Mousikou, Montoya, & Defior, 2013 for a similar approach). The same procedure was used with 30 college students in Israel (Treiman, Levin, et al., 2007) and 20 college students in South Korea. A visual similarity value for each letter was obtained by averaging the similarity values across all pairs including that letter and each other letter of the alphabet. The mean visual similarity ratings were 2.74 (*SD* =.24) for English, 2.76 (*SD* = .28) for Portuguese, 2.95 (*SD* = 1.18) for Korean, and 2.79 (*SD* = .45) for Hebrew.

Data analysis

Explanatory item response modeling (EIRM; De Boeck & Wilson, 2004) was used to examine the relations of letter frequency, alphabet order, and visual similarity to letter-name knowledge in the four languages. The technique is representative of a broad class of item response models and goes by several names (e.g., random item effects models, cross-classified random effects models, item mixed-effects models). EIRM is predicated on each data point being cross-classified by items and individuals. For each language in the present study, letter-name responses (i.e., correct or incorrect knowledge of letter names) were cross-classified by individuals and letters. Our modeling process was largely similar to that of previous studies that have used such doubly explanatory EIRMs for literacy outcomes such as word reading and spelling (e.g., Goodwin, Gilbert, Cho, & Kearns, 2014; Kim, Petscher, & Park, 2016). The doubly explanatory model can be expressed as an integration of a person explanatory model and an item explanatory model. The person explanatory model is given by

$$\begin{aligned} \eta_{pi} &= \theta_p - \beta_i \\ \theta_p &= \sum\nolimits_{j=1}^{j} \vartheta_j Z_{pj} + \theta_p^* \end{aligned} \tag{1}$$

where η_{pi} is the mean of a distribution that has a link, usually a logit or probit link, to the probability $\pi_{pi} = \frac{\exp(\theta_p - \beta_i)}{1+\exp(\theta_p - \beta_i)}$ where π_{pi} is the probability of person p correctly responding to item i; θ_p is the ability level of person p. Z_{pj} is a value for person p on covariate j (j = 1, … J; e.g., a score of 100 on a standardized measure of letter-name knowledge for a given individual in a sample), ϑ_j is the regression weight for the person-level covariate, and θ_p^* is the remaining person effect (i.e., random effect) not explained by Z_{pj} and is $N(0,\sigma^2)$. The item explanatory model is given by

$$\begin{aligned} \eta_{pi} &= \theta_p - \beta_i \\ \beta_i^{=} & \sum\nolimits_{K=1}^{K} \beta_k X_{ik} + \beta_i^* \end{aligned} \tag{2}$$

where β_i is comprised of X_{ik} as a value for item i on item covariate k (k= 1, … K; e.g. the letter frequency of item i), β_k is the regression weight for the item-level covariate, and β_i^* is the random effect for items not explained by the included covariates. β_i in Equation 2 denotes that the linear function β_i is not equal to β_i because the prediction is not perfect (Wilson, De Boeck, & Carstensen, 2008). The doubly explanatory model that integrates Equations 1–2 is

$$\eta_{pi} = \sum\nolimits_{j=1}^{j} \vartheta_j Z_{pj} + \theta_p - \sum\nolimits_{K=1}^{K} \beta_k X_{ik} \tag{3}$$

where each term is as before and β_i from Equation 2 is in place of β_i. The doubly explanatory applications in most previous studies were Rasch explanatory item response models such that the variability in item responses was decomposed to differences between individual and differences between items while keeping the discrimination fixed at 1.0. In the present study, the doubly explanatory model was extended to include fixed effects and a random effect for item discrimination. The inclusion of multiple item random effects then facilitated the decomposition of variance as due to individuals, item difficulties, and item discriminations.

We began by specifying an unconditional model in Mplus 8.1 (Muthen & Muthen, 2014) to estimate the average difficulty and discrimination of each letter name within each language and to calculate the amount of variance due to each of item difficulty and item discrimination via a variance decomposition index (VDI). A VDI can be equivalent to an intraclass correlations (ICCs) in many mixed effects models. ICCs in the EIRMs are computed differently than ICCs in linear mixed effects models (Cho & Rabe-Hesketh, 2011). As such, we opt to call our decomposition statistic a VDI so that the reader sees that its computation is different than a generalized model-based ICC (Petscher, Compton, Steacy, & Kinnon, 2020). The VDI was computed by taking the sum of the person variance, the variance associated with item difficulty, and the variance associated with item discrimination variances and then dividing each respective variance by that sum. The nature of this type of EIRM in Mplus is such that a probit link is used with Bayes estimation using the default priors. In order for the individual item parameters to be estimated and reported as item difficulties and discriminations in the logit form, we used a three-step process. First, the item difficulty and discrimination residuals from the unconditional model were recovered. Second, the individual item difficulty residuals were added to the grand mean difficulty in order to calculate the probit-based difficulty estimates. Third, logit-based discriminations were calculated by scaling the probit loading by 1.701,[3] and item difficulties were obtained by scaling the probit estimates and dividing by the discrimination. Following the estimation of the unconditional model for each language, a conditional model included a standardized measure of item frequency and raw measures of letter order and visual similarity, followed by interaction terms. Because the raw metric of item frequency produced a wide range of possible scores, it was z-scored to improve interpretability of model-based coefficients. Reductions in difficulty and discrimination variances were evaluated using a pseudo-R^2 to determine how much of the variance in each item parameter was explained by letter frequency, letter order, and visual similarity for each language.

Results

Descriptive statistics

Table 1 shows the proportion of correct responses for each language. On average, 89% of the US children knew the name of a given letter of the alphabet (*SD* = 5%). Item difficulty ranged from 73% for V to 99% for O. The other three languages showed more variability in the percentages of correct responses. The average percent correct for Portuguese was 69% (*SD* = 10%), with a range of 45% for Q to 90% for A. The mean percent correct for Korean was 74% (*SD* = 13%), with a range of 30% for ㅍ to 92% for ㅈ. The average percent correct for Hebrew was 54% (*SD* = 13%), with a range of 40% for ט to כ to 87% for א.

Research question 1: relations of letter frequency, letter order, and visual similarity to letter difficulty and letter discrimination

English

The unconditional model was specified for the letter-name knowledge data for each language (Table 3), with random effects for letters and individuals. For English, 70% of item-level accuracy variance was due to between-individual differences [i.e., 1.00/(1.00 + 0.36 + 0.07) = .70], 25% to differences in item difficulty [i.e., 0.36/(1.00 + 0.36 + 0.07) = .25], and 5% to differences in item discrimination [i.e., 0.07/(1.00 + 0.36 + 0.07) = .05]. The average item difficulty and discrimination were −2.60 and 1.78, respectively (Table 3). When converted to logit-based item difficulty and discrimination indices (i.e., −1.50 and 2.94, respectively; see online supplemental materials), the results indicated that US children had an 82% chance of correctly knowing a letter name. The items were all easy (range = −2.56 to −1.08; online supplemental materials). Item discriminations (range = 2.26 to 3.34) indicated that F, K, and L had the highest discriminatory power and that X and O had the lowest discriminatory power.

Conditional model results (Table 4) showed that letter frequency was significantly predictive of item difficulty differences, such that letters with an average letter frequency were associated with a .88 predicted probability of letter-name knowledge, letters with high frequency (i.e., +1 *SD* above the mean) were associated with a .90 probability of letter-name knowledge, and letters with low frequency (i.e., −1 *SD* below the mean frequency) were associated with a .85 probability of letter-name knowledge (see Figure 1). Neither visual similarity nor letter order significantly predicted item-level variance as main effects; however, the inclusion of the three predictors explained 33% of the item difficulty variance and 29% of the item discrimination variance.

Portuguese

Data from the unconditional model for Portuguese (Table 3) showed that the variances in item responses were mostly due to differences between individuals (i.e., 68%), with 29% of the variance due to differences in item difficulties and 3% due to item discriminations. The average estimated difficulty was −1.21, which converted to a logit item difficulty of −0.67 (posterior *SD* = 0.36) with an associated predicted probability of .67. An average item discrimination of 1.77 was estimated, which converted to a logit item difficulty of 2.86 (posterior *SD* = .17). The range of item discriminations in Portuguese (2.53 to 3.18) was similar to that in English. However, the range of item difficulties in Portuguese (−1.44 to 0.17; see Table 4) was more restricted than in English. Conditional model results (Table 4) demonstrated that the mean item difficulty and discrimination when controlling for letter frequency, letter order, and visual similarity were −0.41 and 1.30, respectively. As with English, letter frequency was significantly associated with item difficulty. When letter frequency was average, the

Table 3. Explanatory IRT model with no predictors.

				95% Confidence Interval		
Fixed Effects	Item Parameter	Estimate	Posterior *SD*	Lower Bound	Upper Bound	Visual Discrimination Index
English	Difficulty	−2.60	0.21	−2.99	−2.18	-
	Discrimination	1.78	0.16	1.47	2.09	-
Portuguese	Difficulty	−1.21	0.16	−1.42	−0.81	-
	Discrimination	1.77	0.08	1.59	1.91	-
Korean	Difficulty	−1.02	0.14	−1.27	−0.71	-
	Discrimination	1.31	0.12	1.14	1.61	-
Hebrew	Difficulty	−0.36	0.18	−0.76	−0.01	-
	Discrimination	1.82	0.07	1.67	1.98	-
Random Effects						
English	Difficulty	0.36	0.16	0.15	0.78	0.25
	Discrimination	0.07	0.09	0.04	0.43	0.05
	Person	1.00	-	-	-	0.70
Portuguese	Difficulty	0.43	0.16	0.24	0.82	0.29
	Discrimination	0.04	0.04	0.04	0.20	0.03
	Person	1.00	-	-	-	0.70
Korean	Difficulty	0.43	0.12	0.26	0.75	0.28
	Discrimination	0.11	0.06	0.03	0.26	0.07
	Person	1.00	-	-	-	0.65
Hebrew	Difficulty	0.59	0.24	0.32	1.22	0.36
	Discrimination	0.05	0.03	0.03	0.12	0.03
	Person	1.00	-	-	-	0.61

Table 4. Explanatory IRT model with letter frequency, letter order, and visual similarity as predictors.

				95% Confidence Interval	
Fixed Effects	Item Parameter	Estimate	Posterior *SD*	Lower Bound	Upper Bound
English	*Difficulty*	−2.86	1.46	−5.68	0.07
	Letter Frequency	**0.34**	**0.19**	**0.001**	**0.75**
	Letter Order	−0.03	0.02	−0.07	0.02
	Visual Similarity	0.06	0.52	−0.92	1.12
	Discrimination	1.57	1.33	−1.05	4.21
	Letter Frequency	0.17	0.14	−0.07	0.47
	Letter Order	−0.01	0.02	−0.04	0.02
	Visual Similarity	0.16	0.46	−0.73	1.09
Portuguese	*Difficulty*	−0.41	1.20	−2.71	2.05
	Letter Frequency	**0.45**	**0.16**	**0.17**	**0.79**
	Letter Order	0.01	0.02	−0.04	0.04
	Visual Similarity	0.25	0.37	−0.49	1.04
	Discrimination	1.30	0.72	−0.29	2.66
	Letter Frequency	0.14	0.10	−0.05	0.38
	Letter Order	0.01	0.01	−0.02	0.02
	Visual Similarity	0.13	0.24	−0.30	0.67
Korean	*Difficulty*	−0.92	0.20	−1.32	−0.52
	Letter Frequency	**0.28**	**0.11**	**0.07**	**0.50**
	Letter Order	−0.05	0.10	−0.25	0.15
	Visual Similarity	−0.17	0.11	−0.37	0.05
	Discrimination	1.37	0.18	1.09	1.80
	Letter Frequency	0.11	0.09	−0.06	0.31
	Letter Order	−0.02	0.09	−0.19	0.15
	Visual Similarity	**0.24**	**0.10**	**0.02**	**0.15**
Hebrew	*Difficulty*	−0.60	0.35	−1.28	0.07
	Letter Frequency	**0.29**	**0.17**	**0.03**	**0.64**
	Letter Order	−0.02	0.03	−0.07	0.03
	Visual Similarity	−0.15	0.16	−0.47	0.17
	Discrimination	1.82	0.14	1.55	2.12
	Letter Frequency	0.07	0.06	−0.05	0.20
	Letter Order	0.00	0.01	−0.02	0.02
	Visual Similarity	0.01	0.06	−0.11	0.13
Random Effects					
English	Difficulty	0.24	0.16	0.08	0.69
	Discrimination	0.05	0.09	0.01	0.35
	Person	1.00	-	-	-
Portuguese	Difficulty	0.30	0.14	0.16	0.67
	Discrimination	0.03	0.03	0.00	0.11
	Person	1.00	-	-	-
Korean	Difficulty	0.31	0.11	0.18	0.59
	Discrimination	0.13	0.11	0.03	0.43
	Person	1.00	-	-	-
Hebrew	Difficulty	0.51	0.24	0.27	1.16
	Discrimination	0.05	-	-	-
	Person	1.00	0.03	0.02	0.15

Fixed effect coefficients in bold are statistically significant. Difficulty and discrimination random effect estimates are statistically significant; person random effects are fixed at 1.0.

predicted probability was .58, compared to .49 when frequency was 1 *SD*s below the mean and .65 when frequency was 1 *SD*s above the mean (see Figure 1). Similar to English, only letter frequency was significantly related to the item-level outcomes, yet the inclusion of the three predictors explained 30% of the item difficulty and 25% of the item discrimination variances.

Korean

The unconditional model for Korean (Table 3) showed that 65% of the variance in item responses was due to between-individual differences, 28% was due to item difficulty differences, and 7% was due to item discrimination differences. The mean difficulty and discrimination for Korean letters were −1.02 and 1.31, respectively. When difficulty was converted to the logit scale (Table 4), the average item

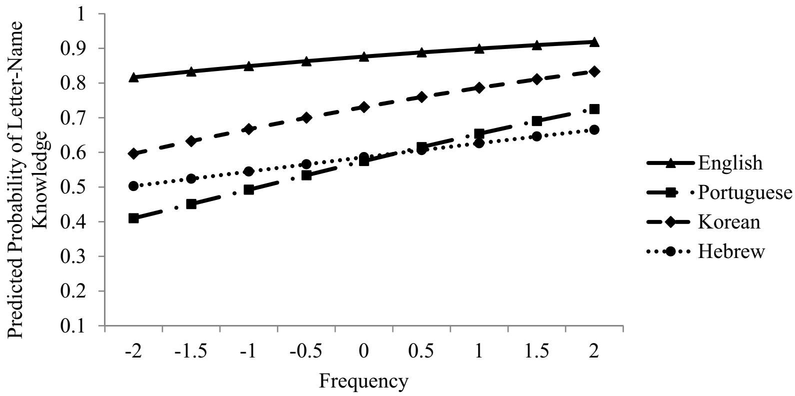


Figure 1. Predicted probabilities of letter-name knowledge conditional on (standardized) letter frequency by language.

difficulty value was −0.78 (posterior *SD* = .63) and was associated with a predicted probability of .69. Conditional model results (Table 4) indicated that letter frequency was significantly associated with item difficulty. The mean difficulty for Korean letters when letter frequency, letter order, and visual similarity were average was estimated as −0.92 (posterior *SD* = 0.20), which converted to a logit-based probability of .73. The significant effect of letter frequency (i.e., 0.28) indicated that one standard deviation increase in letter frequency was associated with a .79 probability of getting an item correct and a one standard deviation decrease in letter frequency was associated with a .67 probability getting an item correct. The mean discrimination was 1.37 (posterior *SD* = 0.18). The inclusion of three predictors explained 28% of the variance in item difficulty and 0% of the variance in item discrimination.

Hebrew

Sixty-one percent of the total variance was due to between-individual differences, 36% was due to item difficulty differences and 3% was due to item discrimination differences. The mean difficulty and discrimination values were −0.36 and 1.82, respectively (Table 3). When converted to logit-based values (Table 4), the average item difficulty was estimated at −0.20 (posterior *SD* = 0.40; predicted probability = 0.55) and the average discrimination was 3.07 (posterior *SD* = 0.31). The item difficulties ranged from −0.70 to 0.90, and the item discrimination values ranged from 2.46 to 3.54. The mean difficulty for Hebrew letters when letter frequency, letter order, and visual similarity were average was estimated as −0.60 (Table 4; posterior *SD* = 0.35), which converted to a logit-based probability of .59. Findings from the conditional model (Table 4) revealed that letter frequency was significantly associated with letter-name difficulties (0.29, $p < .05$). When controlling for the effects of visual similarity and letter order, the range of predicted probabilities for letter-name knowledge across various levels of letter frequency was .55 for low levels of frequency (i.e., −1 *SD*s) to .63 for high levels of letter-name frequency (i.e., +1 *SD*s; Figure 1). The inclusion of letter frequency, visual similarity, and letter order in the model explained 14% of the variance in item difficulty and 0% of the variance in item discrimination.

Post-hoc analyses

The a priori model analyses for Research Question 1 having shown that letter frequency had a consistent, statistical effect on item-level accuracy across languages. It was of interest to isolate the explanatory power of letter frequency through the pseudo-R^2 statistic. Each conditional EIRT was rerun including only including letter frequency. The random effect variance components associated with each item parameter by language were: English (item difficulty = 0.35; item discrimination = 0.08); Portuguese (item difficulty = 0.28; item discrimination = 0.03); Korean (item difficulty = 0.35;

item discrimination = 0.12); Hebrew (item difficulty = 0.51; item discrimination = 0.05). When these variance components are compared to the random effect variance components from the unconditional models (Table 3), results showed that letter frequency explained 3% of the variance in item difficulty [e.g., (0.36–0.35)/0.36 = 0.03] and 0% of the variance in item discrimination in English; 36% of the variance in item difficulty and 25% of the variance in item discrimination in Portuguese, 19% of the variance in item difficulty and 0% of the variance in item discrimination in Korean; and 14% of the variance in item difficulty and 8% of the variance in item discrimination in Hebrew. It is important to note that in several instances of the post-hoc models, such as the Portuguese-language model, the random effect variance components associated with letter frequency only (i.e., 0.28) were smaller than the random effect variance components from the models reported in Table 4 where letter frequency, letter order, and visual similarity were included together (i.e., 0.30). Increasing variances between conditional models is frequently observed in mixed effects models when predictors are weakly or negatively correlated with other variables in the model (Gelman & Hill, 2006).

Research question 2: interactions among letter frequency, letter order, and visual similarity

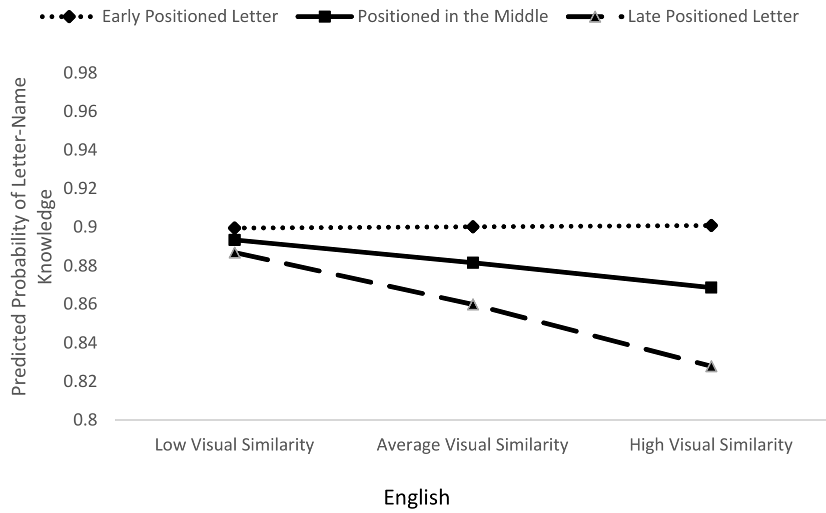
A second set of models was run for each language that included pairwise interactions among letter frequency, letter order, and visual similarity. No significant interactions were observed for either Hebrew or Portuguese. In English, there was an interaction effect for letter difficulty between visual similarity and letter order (−.17, 95% CI = −.35, −.12) at middle and ±1 SD values of the variables such that, for letters with higher visual similarity, those that were earlier in the alphabet (e.g., B) were easier than those that were later in the alphabet (e.g., V; Figure 2a; higher probability values represent higher likelihood of knowing letters). For letters with low visual similarity, letter order did not make a difference in difficulty.

In Korean, an interaction between letter frequency and visual similarity for letter difficulty (Figure 2b; .39, 95% CI = .05, .59) was observed such that for high-frequency letters, those with higher visual similarity were easier than those with low visual similarity, whereas for low-frequency letters, those with lower visual similarity were easier than letters with high visual similarity. In predictions of item discrimination in Korean, there was a significant interaction between letter frequency and visual similarity (.28, 95% CI = .04, .63). Figure 3 shows that, for high-frequency letters, discrimination values were similar across levels of visual similarity. For low-frequency letters, letters with high visual similarity better discriminated between high and low ability individuals (1.85) than letters with low visual similarity (0.51).

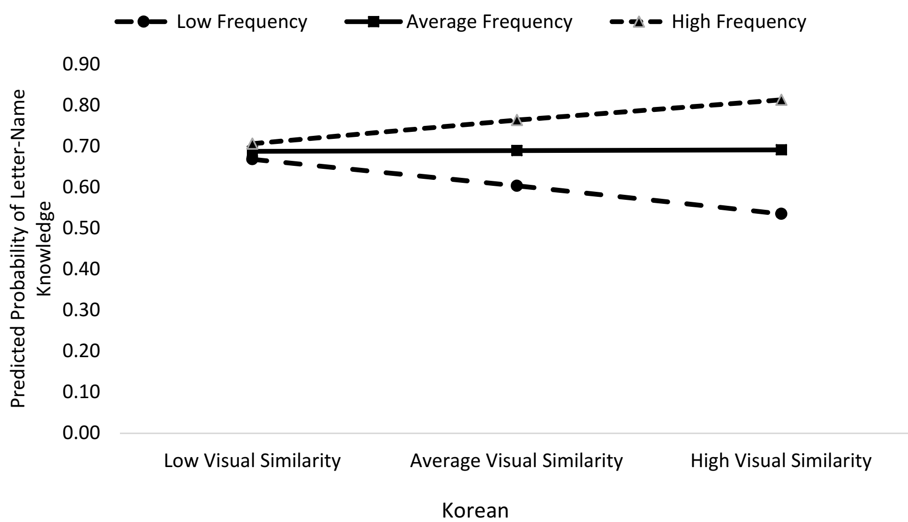
Discussion

The goal of the present study was to identify language- or script-general and specific principles of letter features that contribute to children's letter-name knowledge. To this end, we examined the relations of three-letter features – letter frequency, letter order, and visual similarity – to item difficulty and discrimination in four languages with three scripts (English, Portuguese, Korean, and Hebrew). We found that letters varied in difficulty and discriminatory power in the four languages. While the largest portion of variance in children's letter-name knowledge was attributed to individual differences, substantial variance was found for letter features in letter difficulty and for letter discrimination. The three-letter features explained from a small to moderate amount of the variance in letter difficulty and little to a moderate amount of variance in letter discrimination.

One striking result is that letter frequency was consistently and uniquely related to difficulty of letter names in all four languages when controlling for letter order and visual similarity, with pseudo-R^2 values ranging from 3% in English to 36% in Portuguese. The consistent frequency effect on the difficulty of letter names suggests that which letters are more difficult or easier to acquire is partly a function of how frequently those letters appear in printed materials and consequent exposure to and discussion of the letters. For instance, letters that occur more often in English (e.g., E, T) are relatively



(a)



(b)

Figure 2. Predicted probability of correct letter-name knowledge for (a) visual similarity and letter order interaction in English and (b) visual similarity and letter frequency interaction in Korean. Higher probability values represent higher likelihood of knowing letters.

easy to acquire whereas letters that occur less often (e.g., U, V) are more difficult. As noted earlier, the role of exposure frequency in letter-name acquisition was inconsistent in previous studies (Kim & Petscher, 2013; Treiman et al., 2006; Treiman, Levin, et al., 2007; Turnbull et al., 2010), and it was difficult to make comparisons across studies because of differences in the statistical models used. The consistent findings across four languages with three different scripts in the present study indicate that letter frequency in printed materials, an exposure effect, is likely to be an underlying principle across languages, scripts, and linguistic and cultural environments.

Letter order and visual similarity did not add significant unique explanatory power in letter difficulty in any of the four languages when all three variables were included in the analyses. This

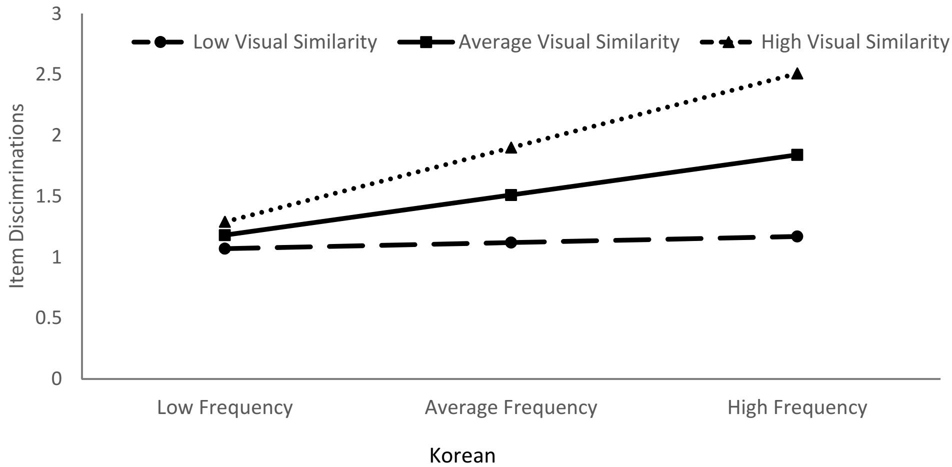


Figure 3. Estimated item discriminations letter frequency and visual similarity interaction in Korean.

might be because the effects of other letter features were accounted for in the present study. Although some previous studies found significant relations of letter order (e.g., Justice et al., 2006; McBride-Chang, 1999) or visual similarity (e.g., Levin et al., 2008; Treiman et al., 2006; Treiman, Levin, et al., 2007) to letter difficulty, most of these studies did not control for all of the other letter features that were considered in the present study. The few studies that included such controls (Huang & Invernizzi, 2012; Treiman et al., 2006) differed from the present study in the operationalization of some letter features and in the outcome, making comparisons with the present study difficult. For example, letter order was a continuous variable in the present study but a dichotomous variable (whether the letter was A, B, or C) in the study of Treiman et al. (2006). The outcome in the present study was the likelihood of knowing the letter, but it was confusions between pairs of letters in the study of Treiman et al. (2006).

The present findings also revealed an interaction between visual similarity and letter order for item difficulty in English. Letters with high visual similarity that were positioned earlier in the alphabet were easier than those positioned later in the alphabet after accounting for the main effect of letter frequency. However, there was no effect of order for letters with low visual similarity. Some previous studies have reported that letters that occur early in the alphabet in English (A, B, & C) are easier than other letters (Huang & Invernizzi, 2012; Justice et al., 2006; McBride-Chang, 1999), and the present findings suggest that the letter order effect is most evident for letters with high visual similarity. Such an effect was not found in the other languages, however, for reasons that are unclear. Therefore, these results must be interpreted with caution and future replications are needed.

Another interaction was found between visual similarity and letter frequency in Korean such that, for letters with high frequency, those with higher visual similarity were easier whereas for letters with low frequency, those with lower visual similarity were easier. One potential explanation for the surprising benefit of high visual similarity for high-frequency letters is based on the fact that the high-frequency letters in Korean are the basic consonant and vowel letters. Basic consonants with high visual similarity to other letters (e.g., ㄱ, ㄴ) may receive more stress in formal and informal learning contexts than those with low visual similarity (ㄹ, ㅇ) because they are earlier in the sequence of basic consonant letters. Similarly, children may perform relatively well on the vowel letter ㅏ, despite its high visual similarity to other letters, because it is the first letter in the basic vowel category. The interaction between visual similarity and letter frequency in Korean would need to be replicated, however, before strong conclusions can be drawn.

Letters in each language differed in discriminatory power, or precision in differentiating children in their letter-name knowledge. However, none of the letter features examined in this study – letter frequency, letter order, or visual similarity – was uniquely or independently associated with item discrimination. We did find a moderation effect in Korean such that, for low-frequency letters, letters with high visual similarity discriminated students' letter-name knowledge better than letters with lower visual similarity. For high-frequency letters, in contrast, visual similarity did not have an impact on discrimination. The majority of low-frequency letters with high visual similarity are double vowel letters, so the interaction suggests that knowledge of double vowel letters discriminates children's letter name knowledge in Korean better than knowledge of other letters. This is the first study to examine the role of letter characteristics in item discrimination for letters, and more research is needed to determine why letters differ in discriminatory power.

Although the present results are informative, this study has several limitations. One limitation is inherent in any secondary data analysis: There were differences in study characteristics such as sample sizes, age ranges, socio-economic backgrounds of children, and letter-name knowledge assessment procedures, and we do not have detailed information about children's language and print-related experiences and cultural differences in letter-name teaching. Future endeavors can investigate whether and how differences in these factors influence children's learning of letter names across languages and scripts. A second limitation is that, in order to allow for comparisons across the four languages, the present analyses did not account for how letters in Korean are classified into four categories. When this was considered in prior work with Korean children, letter-name knowledge was found to differ as a function of category (Kim & Petscher, 2013). A further limitation is that some potentially relevant factors were not included in the present study, including those related to the phonological forms of letter names and the letters contained in the child's own name. These appear to play a role in letter name learning and should be accounted for in future studies (Huang & Invernizzi, 2012; Justice et al., 2006; McBride-Chang, 1999; Piasta & Wagner, 2010; Treiman, Cohen, Mulqueeny, Kessler, & Schechtman, 2007; Treiman & Kessler, 2003; Treiman, Kessler, & Bourassa, 2001; Treiman et al., 2006; Treiman, Levin, et al., 2007; Turnbull et al., 2010). It will also be valuable to replicate the present study using other measures of visual similarity. Finally, it is important to note that the base rate of letter name knowledge accuracy varied across language. Summary statistics in generalized linear models, such as pseudo-R^2 values, can be biased according to the size of the base rate (Menard, 2000). Comparisons among languages should be informed by this known relation.

Given the importance of letter-name knowledge in literacy acquisition in languages with alphabetic writing systems (Adams, 1990; Foulin, 2005; Kim, 2011; Levin, Shatil-Cameron, & Asif-Rave, 2006), lack of letter knowledge is a risk factor in early literacy acquisition. The present findings suggest that exposure to letters as measured by letter frequency is a language-general mechanism in the learning of alphabet letters. Future work is warranted on other potential aspects of learning that might be general across languages, scripts, or cultures, and those that are specific to particular languages, scripts, or cultures.

Notes

1. Data are available upon request.
2. In South Korean dictionaries, a double consonant or vowel letter immediately follows its basic counterpart.
3. This value is a constant used to scale probits to logits (see Camilli, 2017).

Disclosure statement

The authors declare there is no conflict of interest.

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