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Phonological Assimilation and Visual Word Recognition

Yang Lee · Miguel A. Moreno · Hyeongsaeng Park · Claudia Carello · Michael T. Turvey

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Abstract Are the visual word-processing tasks of naming and lexical decision sensitive to systematic phonological properties that may or may not be specified in the spelling? Two experiments with Hangul, the alphabetic orthography of Korea, were directed at the effects of the phonological process of assimilation whereby one articulation changes to conform to a neighboring articulation. Disyllabic words were responded to more quickly when (a) the final letter of the first syllable and the initial letter of the second syllable specified phonemes that satisfied rather than violated consonant assimilation, and (b) the vowel letters specified harmonious as opposed to disharmonious vowel phonemes. Discussion addressed the possible mediation of assimilation effects by consistency differences and theories that predict broad phonological influences on visual word recognition.

Keywords Assimilation · Phonology · Korean word recognition

Introduction

It is now well understood that the phonology of a printed or written word plays a key role in the processes by which the word is identified (e.g., Frost, 1998, Lukatela, &

Y. Lee (✉)
Gyeongsang National University, Jinju, South Korea
e-mail: yangleepsy@hanmail.net

Y. Lee · M. A. Moreno · H. Park · C. Carello · M. T. Turvey
Haskins Laboratories, 300 George Street,
New Haven, CT, 06511, USA

M. A. Moreno · H. Park · C. Carello · M. T. Turvey
University of Connecticut, Storrs, CT, USA

M. A. Moreno
e-mail: miguel.moreno@uconn.edu

Turvey, 1998, Tan, & Perfetti, 1998, Van Orden, & Goldinger, 1994). This understanding is embodied in the closely related *phonological coherence hypothesis* (Lukatela, Frost, & Turvey, 1999, Van Orden, & Goldinger, 1994, Van Orden, Pennington, & Stone, 1990) and *universal phonological principle* (Perfetti, & Zhang, 1995, Perfetti, Zhang, & Berent, 1992). In the hypothesis, what is presumed to be most coherent, most consistent among a word's codes is phonology. In the principle, what is presumed to be universal is the automatic, "reflexive" activation of a word's phonology—its constituent phonemes and pronunciation—for all writing systems (alphabetic, syllabic, and logographic) and most words.

The central argument underlying the hypothesis and principle is that the mappings among orthographic, phonological and semantic structures are not equally precise, not equally deterministic. The most systematic mapping, that which is most nearly one-to-one, is assumed to be between orthographic structure and phonological structure. A nearly one-to-one mapping means that resonance or self-consistency will be achieved rapidly within the weighted connections linking the processing units of the two structures. As expressed in adaptive resonance theory (Grossberg, 1982, Grossberg, & Stone, 1986), a resonant mode is achieved when the activity excited in a given layer of processing units from below matches that excited from above. In the latter perspective the stricter mapping of orthography to phonology means that phonological forms are coded at the outset closest to their final forms (their respective attractors). As a result, they will be the earliest codes to achieve resonance or coherence (Gottlob, Goldinger, Stone, & Van Orden, 1999, Van Orden, & Goldinger, 1994, Van Orden et al., 1990). One might argue, therefore, that the quickly attained coherence of phonological codes sets them apart from other codes, placing them in the position of playing a key role in facilitating (mediating) the coherence and stability of other ongoing linguistic processes.

In intuitive terms, form–form mappings are faster than form–meaning mappings because the latter involve probabilistic elements to a larger degree. There are two primary empirical manifestations of this asymmetry in mappings. One is the tendency for semantics to be activated later than phonology (e.g., Lukatela, Carello, Savić, Urošević, & Turvey, 1998a), especially for words in isolation and more so for words that are particularly vague (e.g., Perfetti, & Tan, 1998, Tan, & Perfetti, 1998). The other is the evidence, obtained from experiments on masked priming, that the lower limit on processing time in both naming and lexical decision is set by the time scale of resolving a word's phonology (e.g., Lukatela, & Turvey, 1998, Lukatela et al., 1998a, 1999).

The present research was directed at furthering understanding of the phonological code implicated in the coherence hypothesis and universality principle. Specifically, the research was directed at the proximity of the code to that required for speech production.

The phonological manipulations conducted in past investigations of visual word recognition have focused primarily upon the grapheme–phoneme mapping identified above. Recently, however, the question has been raised of whether there are detectable influences on visual word recognition (as measured by naming and lexical decision) due to manipulation of the systematic phonological constraints identified in phonological theory (e.g., Berent et al., 2001). These constraints on the spoken language express the orderly variations in consonants and vowels as a function of their (within-word) location relative to other consonants and vowels. Phonological theories often assume that a spoken word's lexical representation under-specifies the phonological form of the word's pronunciation (Archangeli, 1984, Borowsky, 1986).

Only those properties particular to a word's phonological segments are specified in the lexicon. The constraints that apply generally are separate from the word's lexical form and are imposed upon that form in generating the phonology appropriate for speech.

Berent et al. (2001) investigated the Obligatory Contour Principle (OCP; McCarthy, 1986) that prohibits adjacent identical elements in the phonological sequence representing a word in the internal lexicon. In Hebrew, words are formed by the insertion of roots into letter patterns. The roots are typically consonant triplets that often embed geminates. An example is the repeated consonants in the root *bdd*. For such a root, the OCP proscribes the storage of the geminates: *bd* is presumed to be stored rather than *bdd*. The geminates, therefore, can only arise in the processes that transform the lexical representation into the speech-appropriate form. The specifics of the hypothesized rightward productive process are such that the emergence of the geminates is restricted to the root's final position. Accordingly, root-final geminates are classified as well formed relative to root-initial geminates (that occur rarely in Hebrew). In a lexical decision task, Berent et al. (2001) found that nonwords constructed from novel roots with root-initial gemination were rejected faster than nonwords with root-final gemination. They interpreted this outcome as suggesting that accounts of visual word recognition must go beyond traditional considerations of grapheme–phoneme relations to include considerations of linguistic competence. Echoing a growing sentiment (e.g., Liberman, & Liberman, 1990, Perfetti, 1992), they conjectured that both fluent and non-fluent visual word recognition must be explained ultimately in terms of the "interaction of decoding skills and linguistic knowledge (p. 644)."

In the present research we posed the question of whether phonological constraints influence visual processing in Korean Hangul. Korean writing was invented in the 15th century. Its explicit purpose was to encode phonetic, phonological, and morphological properties in an alphabetic system (*Hangul*) in which the syllable plays a strong visual and functional role. In the Korean alphabetic script, symbols represent each of the phonemes. Phonemes that are related with respect to articulation are visually similar (e.g., /k/, /k′/, and /k^h/ are transcribed as ㄱ, ㄲ, and ㅋ, respectively). The symbols are typically joined into syllables with the onset consonant and the vowel of each syllable written in the upper half (consonant at top left, vowel at top right) and the syllable's coda consonant written in the lower half. Because the Korean alphabetic writing system is morphophonemic, consistent pronunciation of letter–symbols is sometimes sacrificed in order to preserve morphological consistency, with the syllable boundary playing an important role in various phonological changes.

The phonological constraint we investigated was *assimilation*. The process of assimilation refers to a change in one articulation in order to conform more closely to an immediately or nearly adjacent articulation. Assimilation is perhaps the most widely occurring type of phonological constraint (Clements, & Hume, 1995). We investigated two kinds of assimilation. In two-syllable Korean words the final consonant of the first syllable is often assimilated for ease of pronunciation according to the initial consonant of the second syllable. For example, all non-nasal consonants (except for /l/ written as ㄹ) are nasalized when they are contiguous to syllable-initial nasal consonants (e.g., /n/ written as ㄴ) and syllable-final nasal consonants /n/

are lateralized[1] when contiguous with syllable-initial lateralized consonants (e.g., /l/ written as ㄹ). The influence on visual word recognition of this phonological constraint on consonants was evaluated in Experiment 1.

Another kind of assimilation in Korean is vowel harmony, which is a restriction on the vowels that occur in successive syllables. Generally, a vowel harmony system can be defined as one in which the vowels of a language divide into two or more (possibly overlapping) subsets, with the condition that all the vowels in, say, a word must come from a single such subset (Goldsmith, 1990). The harmony subsets in Korean are positive or front (/a/, /ya/, /o/, /yo/ respectively, ㅏ, ㅑ, ㅗ, ㅛ), negative or back (/eo/, /yeo/, /u/, /yu/, respectively, ㅓ, ㅕ, ㅜ, ㅠ), and neutral (/eu/, /i/, respectively, ㅡ, ㅣ). A Korean word is more easily pronounced if the vowels in two successive syllables are of the same vowel type (e.g., in 반장 both syllables have the same positive vowel, ㅏ) or if one is a neutral vowel. It is difficult, for example, to proceed from a front (ㅏ) to a back vowel (ㅓ) (e.g., as in 반장 pronounced /pan-tsaŋ/). Nonetheless, vowel disharmony in modern Korean nouns is popular and acceptable (in contrast to the general tendency to prohibit disharmony, for example, in languages of the Altie family). It preserves morphological relatedness at the cost of pronunciation simplicity. Harmony plays a particularly important contemporary role in the onomatopoetic and mimetic words that occur frequently in the language. The effect of harmony and disharmony on visual word recognition was evaluated in Experiment 2.

In both experiments, the basic comparisons were made between two sets of printed Hangul words that were closely matched on variables (e.g., familiarity, neighborhood size) that correlate with typical response measures. Each word in each set was composed of two consonant–vowel–consonant syllables (or two Hangul syllable-blocks, Taylor, & Taylor, 1983). The two sets of words differed as to whether or not their component letters transcribed the phonological constraint in question. In both cases, the designation "plus" + is used when the production constraint is respected in the orthography; the designation "minus" − is used when the production constraint is absent in the orthography. In the case of consonant assimilation (CA), words designated CA+ were those for which the phonemes corresponding to the first-syllable final letter and the second-syllable initial letter were assimilated. That is, pronunciation of CA+ words is completely constrained by the orthography. Words designated CA− were words for which the final letter of the first Hangul block did not represent a phoneme assimilated to the phoneme represented by the first letter of the second Hangul block. That is, pronunciation of CA− words requires a change in articulation at the syllable boundary. Within this latter set, the phonology of a word's pronunciation is a systematic transformation of the phonology of the word as specified by its component letters. In the case of vowel assimilation (VA), words designated VA+ were those for which the phoneme corresponding to the vowel letter of the second syllable was harmonious with the phoneme corresponding to the vowel letter of the first syllable. Words designated VA− were words for which the vowel letters represented disharmonious phonemes. For either CA or VA, an observed difference between the two sets of words (CA+ vs CA−, VA+ vs VA−) in speed and accuracy of recognition

[1] A lateral is typically defined as a sound that is produced by an occlusion somewhere along the mid-sagittal line of the vocal tract with airflow around one side or around both sides of the occlusion. In Korean, lateralization refers to the transformation to a lateral consonant from a nasal consonant that was subsequent to a lateral consonant.

a 반란

b 반장

Fig. 1 (Top) A disyllabic word of the form CA− because the pronunciation of ㄴ is altered to fit ㄹ (i.e., [pa*l*-lan] instead of /pa*n*-lan/). (Bottom) A disyllabic word of the form CA+ because the pronunciation of ㄴ need not be altered to fit ㅈ (i.e., /pan-tsaŋ/)

would be reason to consider that the Korean readers in the experiments were affected implicitly by the surface phonological forms appropriate for speech production.

Experiment 1

Two examples of Korean words are shown in Fig. 1a, b. The first syllable-block of both words has the same final letter ㄴ representing the same final nasal consonant /n/. In respect to the second syllable-block, the initial letter ㄹ in the word 란 depicted in Fig. 1a maps to a lateralized consonant /l/ and the initial letter ㅈ in the word 장 depicted in Fig. 1b maps to a non-lateralized consonant /ts/. In pronouncing the word, 반란 in Fig. 1a, the final letter of the first syllable-block (ㄴ) must be read as a consonant ([l]) in lateral agreement with the initial consonant of the second syllable: [pa*l*-lan] instead of /pa*n*-lan/. In pronouncing the word반장depicted in Fig. 1b, no transformation of the phonemic interpretation of the first syllable's final letter is required: /pan-tsaŋ/. To summarize, the word, 반장, depicted in Fig. 1b does, and the word, 반란, depicted in Fig. 1a does not, transcribe the consonant assimilation of pronunciation. The disyllabic word 반장, depicted in Fig. 1b, is an example of CA+; the disyllabic word 반란, depicted in Fig. 1a, is an example of CA−.

As noted above, theories of phonology in linguistics often assume that a spoken word's lexical representation under-specifies the phonological form of the word's pronunciation. The lexicon includes only those properties particular to a word's phonological segments. General constraints such as assimilation are distinct from the word's lexical form. They are imposed upon that form post-lexically in the generation of the phonology appropriate for speech. Making parallel assumptions for the written word leads to the hypothesis that the determination of the complete phonological code involves fewer steps in CA+ words than CA− words. Accordingly, one might expect response latency (lexical decision, naming) to be shorter for CA+ words than CA− words if the response is mediated by the full phonological code. A similar expectation might follow from other perspectives. For example, in connectionist-inspired models that emphasize feedforward–feedback dynamics the spelling-to-pronunciation (feedforward) and pronunciation-to-spelling (feedback) mappings are congruent in the case of CA+ words and incongruent in the case of CA− words. Such models would predict earlier stabilization of the mediating phonological code for the congruent case resulting in shorter response latencies (e.g., Stone, Vanhoy, &Van Orden, 1997, Van Orden, & Goldinger, 1994).

Method

Participants

Eighty undergraduates at Gyeongsang National University in Korea participated in partial fulfillment of a course requirement. They were assigned to the naming or lexical decision groups according to their appearance at the laboratory. (In lexical decision, participants pressed a key to indicate whether the visually presented letter string was a word or not. In naming, participants spoke aloud the visually presented letter string.)

Stimuli

A total of 48 disyllabic Hangul words were chosen, with 12 words in each of four familiarity (high vs low) × consonant assimilation (CA+ vs CA−) cells. Familiarity was determined by a different group of 50 participants, who rated a larger set of words from 1 (not very familiar) to 7 (very familiar). The mean of the high familiarity words was 4.5 ± .40 and the mean of the low familiarity words was 2.4 ± .55. The high and low familiarity words differed reliably in terms of word frequency. Word frequency was estimated from a database with a corpus of over 51 million Korean words that was developed by the Korean Advanced Institute of Science and Technology (KAIST, 1999). The average frequency counts for high and low familiarity words were 954.25(±1,349) and 17.5(±31), respectively, $t(46) = 3.4$, $p < .01$. The average frequency counts for CA+ and CA− words were 530(±1,025) and 442(±1,107), respectively, $t(46) = .29, p > .10$. All words were composed of two consonant–vowel–consonant syllables. The majority of the words were vowel harmonious with a small number of vowel disharmonious words that were equally distributed between the two CA conditions for words and nonwords. Each syllable in a disyllabic word was itself a word. For all members of the CA− set, the final consonant of each first syllable was either ㄴ, ㅂ or ㄱ. For the CA+ set, the final consonant of most of the first syllables was either ㄴ, ㅂ or ㄱ. A small number of words ended in the final consonant ㅇ (a consonant that also varies in its spelling–pronunciation mapping).

Stimuli were evaluated further with respect to neighborhood size. To determine neighborhood size for familiarity, a different group of 300 participants were asked to list unique two-syllable words that could be constructed by combining other syllable blocks with either the first or second syllable block of the target stimuli. An Assimilation × Familiarity neighborhood analysis revealed that CA− words had fewer neighbors (1.50) than CA+ words (2.79), $F(1,44) = 5.00$, $MSE = 20.02$, $p = .03$. The number of familiarity neighbors did not differ as a function of familiarity, nor did familiarity interact with assimilation, Fs < 1.

Neighborhood size was also determined using the KAIST database (KAIST, 1999). For a given target word, neighborhood size was defined as the total number of two syllable words whose first syllable block was the same as the target's. Neighborhood frequency was determined by the summed frequency of all two-syllable words in that neighborhood. Neighborhood size and summed frequency for high and low familiarity words were 139(±50) and 22,623(±16,367) and 118(±78) and 13,801(±17,764), respectively. Neighborhood size and summed frequency for CA+ and CA− words were 139(±60) and 18,218(±17,137) and 118(±70) and 18,206(±18,176), respectively.

Neither neighborhood size nor neighborhood frequency showed a reliable effect or interaction in an Assimilation × Familiarity analysis (Fs < 1).

A corresponding set of 48 nonwords was created from a different set of 48 words similarly ranked for high and low familiarity. The nonwords were created primarily through vowel changes that, in each case, preserved the word status of the component syllables. These disyllabic nonwords composed from monosyllabic words similarly constituted two sets, CA− and CA+, with the same set of final consonants in the first syllables. The neighborhood analysis of nonwords (where familiarity refers to the familiarity of the source word) revealed no differences, all Fs < 1 (CA− nonwords averaged 1.88 neighbors; CA+ nonwords averaged 1.83 neighbors). Additionally, nonword selection was constrained by the requirement that neither CA+ nor CA− stimuli were pseudohomophones. This constraint was met perfectly for CA− and almost perfectly for CA+. For CA+ nonwords, some of the stimuli were unavoidably (given the other constraints) nonwords that sounded like words.

Procedure

Letter strings were presented one at a time on a PC monitor, subtending 2° of visual angle (characters fit inside a 1 × 0.4 cm rectangular space). Presentation of stimuli was controlled by a 486 PC programmed in PASCAL. Instructions were read off the monitor and followed after a delay of 1 min by a practice session that introduced participants to the mechanics of the experiment. A fixation circle appeared on the screen for 500 ms, followed by the target that remained on the screen until a response. This was followed by a blank screen for 500 ms, a string of circles for 500 ms, and then a blank screen for 2 s before the next stimulus appeared. Practice consisted of 24 trials equally distributed among the four cells. Following an interval of 1 min, the experimental session began with the same procedure. The 96 experimental trials were completely randomized. Lexical decision was indicated by a keyboard response. A microphone with a threshold adjustment was used to record the naming response.

Results

Mean latencies and mean percent error for words and nonwords, respectively, are provided in Tables 1, 2. For CA− nonwords, incorrect pronunciations were those that violated the consonant assimilation requirements. An analysis of variance (ANOVA) on latency and error was conducted with task (naming or lexical decision) as a between-subjects variable, and consonant assimilation (CA+ or CA−) and familiarity (high or low) as within-subjects variables.

Word Analysis

The primary expectation was that CA− words would be responded to more slowly and/or with less accuracy than CA+ words. The mean latencies for CA+ and CA− words were 758 and 774 ms, respectively. The mean errors for CA+ words and CA− words were 6.8 and 12.7%, respectively. The latency difference was significant by subjects F_1 and items F_2: $F_1(1,78) = 12.70$, $MSE = 1619.87$, $p < .001$, $F_2(1,44) = 6.05$, $MSE = 1046.91$, $p < .02$. The error difference was not significant (both Fs < 1). Table 1 suggests, however, that the CA influence on latency

Table 1 Mean latency (RT) and percent error (%*E*) for word stimuli as a function of consonant assimilation (CA), task, and familiarity in Experiment 1

Familiarity	Task							
	Naming				Lexical decision			
	CA−		CA+		CA−		CA+	
	RT	%*E*	RT	%*E*	RT	%*E*	RT	%*E*
Low	767	3.5	767	3.5	850	37.9	822	18.8
High	727	1.7	731	1.9	751	7.9	710	3.3

Table 2 Mean latency (RT) and percent error (%*E*) for nonword stimuli as a function of consonant assimilation (CA), task, and source word familiarity in Experiment 1

Familiarity	Task							
	Naming				Lexical decision			
	CA−		CA+		CA−		CA+	
	RT	%*E*	RT	%*E*	RT	%*E*	RT	%*E*
Low	796	4.2	799	5.0	849	20.8	824	18.3
High	774	5.0	789	5.0	823	15.8	816	21.7

was strongly task dependent. This suggestion was borne out by the ANOVA. Task by CA was significant for latency, $F_1(1,78) = 16.38$, $MSE = 1619.87$, $p < .0001$, $F_2(1,44) = 6.91$, $MSE = 1088.84$, $p < .02$, and error, $F_1(1,78) = 80.55$, $MSE = 0.51$, $p < .0001$, $F_2(1,44) = 7.89$, $MSE = 7.43$, $p < .01$, revealing that the contrast between CA+ and CA− for both measures was greater in lexical decision than naming (see Table 1). In the error analysis there was a suggestion that the dependency of CA on task was affected by familiarity, $F_1(1,78) = 18.53$, $MSE = 0.80$, $p < .0001$, $F_2(1,44) = 3.65$, $MSE = 7.43$, $p < .065$. In fact, the pattern of error rates in the lexical decision task (see Table 1) reflected the order (lowest to highest) of average word frequency: CA−/low familiarity = $4(\pm 6.3)$, CA+/low familiarity = $31(\pm 39.5)$, CA−/high familiarity = $879(\pm 1,463)$, and CA+/high familiarity = $1,029(\pm 1,285)$.

Nonword Analysis

CA was not a main effect in either the latency or error analysis (Fs < 1 in both cases). With respect to latency, the interaction of task and CA was significant by subjects: $F_1(1,78) = 11.45$, $MSE = 12,362.88$, $p < .001$, but not by items, $F_2(1,44) = 1.62$, $MSE = 4482.67$, $p > .05$. The significance of F_1 alone might, however, be sufficient to draw the inference of a task-dependent CA effect given that CA+ and CA− nonwords were highly constrained and matched on major variables affecting the response measures (Raaijmakers, Schrijnemakers, & Gremmen, 1999). Focusing on the subjects analysis, CA− was slower by 16 ms in lexical decision, $F(1,39) = 8.55$, $p < .01$, and faster by 11 ms in naming (but not significantly so), $F(1,39) = 3.29$, $p = .08$. No other interactions reached significance by either subjects or items. With the exception of task, $F_1(1,78) = 112.15$, $MSE = 1.10$, $p < .001$, $F_2(1,46) = 5.92$, $MSE = 36.50$, $p < .02$ (with more errors on lexical decision than on naming), there were no effects in the analysis of nonword errors.

Discussion

At issue was whether a difference between two sets of written words at the level of systematic phonology would materialize as a difference in the speed and accuracy with which those words were processed in standard visual word recognition tasks. The results of Experiment 1, an experiment that manipulated consonant assimilation, suggest that visual word recognition performance could indeed be sensitive to differences in systematic phonology.

From the perspective of formal phonology, one might expect CA− stimuli to be associated with slower responding than CA+ stimuli because determining the phonological codes of CA− stimuli requires an additional step of nasalization or lateralization. Similarly, from the perspective of top down-bottom up resonance accounts, longer latencies to CA− stimuli would be expected because, compared to CA+ stimuli, time-to-stabilize the mediating phonological code is prolonged. These particular variants of the general hypothesis of phonological mediation apply equally to naming and lexical decision but were confirmed only for lexical decision. The dependence on task invites an examination of the CA− and CA+ stimuli for differences beyond or other than assimilation, differences that might be less influential in naming than in lexical decision. In particular, it helps to ask how the present manipulation in Hangul relates to conventional distinctions known to affect visual word recognition in English.

Regular English words—words that conform to grapheme–phoneme correspondence rules—can differ in consistency. That is, they can differ in whether or not they include letter patterns that are pronounced differently in other words. There is some research to suggest that English visual word recognition is affected by the degree or strength of consistency. In a series of experiments conducted to determine the precise source of consistency effects, Jared, McRae, and Seidenberg (1990) showed that performance to low frequency inconsistent words was dependent on the relative frequencies of words pronounced the same way ("friends") and words pronounced differently ("enemies"). Latencies and error rates on inconsistent words that were low on the summed frequency of friends and high on the summed frequency of enemies were hindered compared to consistent control words. In contrast, inconsistent words that were high on the summed frequency of friends and low on the summed frequency of enemies did not show a consistency effect relative to consistent control words. Jared later showed that naming performance to high frequency inconsistent words similarly depended on the relative frequencies of friends and enemies (Jared, 1997). The implication is that any consideration of performance on inconsistent words must be grounded in the notion of strength of the spelling–pronunciation mapping.

The KAIST database permits an approximate analysis of spelling-to-pronunciation consistency for CA+ and CA− words. The database lists the frequency count of all disyllabic words given an initial syllable block. All disyllabic Korean words that shared the same spelling–pronunciation mapping as the first syllable block of the target stimuli were considered friends. Disyllabic words that did not share the same spelling–pronunciation mapping as the first syllable block of the target stimuli were considered enemies. An enemy is exemplified by how the same initial syllable block in Fig. 1a, b (i.e., 밥) maps onto two different pronunciations. The number of friends and enemies per target item and their summed frequency were submitted to an Assimilation × Familiarity × Consistency analysis where Consistency was a within item variable with two levels (friends, enemies). The analysis revealed reliable

Assimilation × Consistency interactions for both the number of friends, $F(1,44) = 153.67, p < .01$ and their summed frequency, $F(1,44) = 46.35, p < .01$. The number of feedforward friends was reliably larger than the number of enemies for CA+ words (135 ± 60 vs 4 ± 5) whereas the reverse was true for the CA− words (11 ± 7 vs 106 ± 67). Similarly, the summed frequency of the feedforward friends was reliably greater than the summed frequency of the enemies for CA+ words ($18,000 \pm 17,136$ vs. 217 ± 634), $F(1,44) = 104.0, p < .01$, whereas the reverse was true for the CA− words ($1,451 \pm 2,767$ vs $16,755 \pm 17,750$), $F(1,44) = 53.8, p < .01$. The only other reliable effect was a main effect of consistency for the number of friends, $F(1,44) = 4.1$, $p < .05$. Across all words, the number of friends was reliably greater than the number of enemies (73.4 vs 54.9).

The present finding that responses to CA− words were slower than to CA+ words is congruent with the observation that the spelling-to-pronunciation consistency effect is strongest when summed frequency of friends is low and summed frequency of enemies is high (Jared, 1997; Jared et al., 1990). As the above analysis suggests, CA− words exhibited the latter pattern of friends and enemies, the pattern that appears to maximize inconsistency. In contrast, CA+ words exhibited the opposite pattern. In the typical comparison, inconsistent words of varying degrees of strength are compared with consistent control words. In the present experiment, consistent control words are absent. Only the direct contrast between CA− and CA+ can serve as a measure of the consistency effect. The near zero difference between CA− and CA+ naming latencies conforms to the near zero difference evident in Jared (1997) data (see Experiment 3 and Fig. 3) between inconsistent words dominated by enemies and inconsistent words dominated by friends. Further, the difference between the CA− vs CA+ contrasts in naming and lexical decision in the present experiment is in the same direction as that reported by Ziegler, Montant, and Jacobs (1997) for French words distinguished by spelling-to-pronunciation consistency. Ziegler et al, found a consistency advantage of 16 ms for naming in contrast to a consistency advantage of 35 ms for lexical decision.[2]

Although the idea of strength of consistency may help the understanding of the present task-dependent results, there are reasons for supposing that the contrast between CA− and CA+ words does not reduce to a consistency contrast. Given the articulation-based distinction between CA− and CA+ words, the consistency-based distinction between CA− and CA+ words necessarily follows. That the consistency difference is more properly understood as an artifact of the assimilation difference is reinforced by further analysis of the spelling-to-pronunciation mappings in CA− and CA+ words.

For CA− words, articulation of the first syllable changes when the second syllable begins with a specific letter(s). Consonant assimilation occurs for the example of Fig. 1a when the second syllable begins with the consonant symbolized by the letter ㄹ. Of the 19 consonants represented in Hangul, the consonant symbolized by the letter ㄹ is the only one that requires assimilation of the preceding ㄴ consonant.

[2] A variant of spelling-to-pronunciation consistency has been shown to influence naming of disyllabic words in English (Chateau & Jared, 2000). The consistency variant in question is that of the body of the BOSS (Taft, 1979). For a word such as MEADOW, the segment MEAD is the BOSS and the segment EAD is the body of the BOSS. Disyllabic words with consistent body of the BOSS were named faster in the subjects' analysis than disyllabic words with inconsistent body of the BOSS. In the present Experiment 1, consistency was based on the first syllable. The first syllables of the Hangul stimuli fit the definition of the BOSS and not the definition of the body of the BOSS. All first syllables were consonant–vowel–consonant in composition and morphemic units (they were words).

From the perspective of consistency, the important question concerns the frequency (f) that ㄹ occurs as the first consonant letter following ㄴ relative to the frequency with which the other 18 consonant letters follow ㄴ. For friends to exceed enemies in CA− words such as 반란, the following inequality must hold: $f(ㄹ) \geq \Sigma(f(X_i))$ (where X_i is a member of the 18 consonants and i ranges from 1 to 18). Although, it is unlikely that all 19 consonants will follow the letter ㄴ with equal frequency, the bias is certainly against CA− words. This bias virtually guarantees that CA− words with ㄴ first-syllable final-consonant will have more enemies than friends. (A slightly reduced negative bias would occur when the first-syllable final-consonant is a non-nasal consonant because there are three consonants instead of just one that require assimilation.)

In like fashion we can consider the consistency of CA+ words. The consistency bias in this case follows from the fact that consonant assimilation will occur only when the final consonant of the *first* syllable is either a non-nasal consonant (except for ㄹ) or a nasal-alveolar (ㄴ). The latter conditions include 12 of the 19 Korean consonants. This final-consonant bias of the first syllable is further complicated by the initial-consonant bias of the second syllable. Together, these biases make it unlikely that CA+ words will have more enemies than friends.

In sum, the consistency reported above seems to be inextricably confounded with consonant assimilation. The different mapping from spelling-to-pronunciation that distinguishes CA− from CA+ is a consequence of the constraints on articulation. The same conclusion follows from the data on naming CA− nonwords. In English language studies, nonwords like BINT derived from inconsistent words like PINT are named slower than nonwords like BINK derived from consistent words like PINK (Glushko, 1979). Moreover, pronunciations of nonwords like BINT tend to rhyme with MINT rather than with PINT. If the effect of consonant assimilation in the present experiment was simply an effect of consistency, then (a) naming latencies should have been longer for CA− than CA+ nonwords, and (b) pronunciations of CA− nonwords should have been incorrect, that is, not assimilated. In contrast to these consistency predictions, naming latencies to CA− and CA+ nonwords did not differ and 88% of the pronunciations of CA− nonwords reflected the assimilation transform.

Experiment 2

The association of assimilation and consistency that marks the distinction between CA− and CA+ words does not mark the distinction between VA− and VA+ words. The determination of VA− and VA+ words is based on whether the two vowels composing the disyllabic word are from different classes or from the same class, respectively. In either case, because the spellings of Korean vowels are not context dependent (in contrast to English vowels), there is no attendant letter-to-phoneme inconsistency. Further, the vowel harmony requirement in the spoken language is not universal, as noted. Disharmony is tolerated if it facilitates morphological analysis of the component monosyllabic words. Such is the case for VA− words. They are the written forms of spoken words that are tolerably disharmonious. The upshot is that the contrast of VA− and VA+ words is an example of a difference in assimilation that is not associated with a systematic difference in spelling-to-pronunciation consistency.

In Experiment 2, nouns chosen to vary with respect to both VA and CA were evaluated by the two latency measures. Given the outcome of Experiment 1, there were reasons for expecting that manipulations of VA might affect naming and lexical decision differently from manipulations of CA. Where CA+ and CA− stimuli differ in assimilation and in terms of spelling-to-pronunciation consistency (with CA+ more consistent than CA−), VA+ and VA− stimuli differ only in terms of inter-syllable compatibility of articulation (with VA+ greater than VA−). To the extent that these dimensions have different implications for naming and lexical decision, an interaction between task, CA and VA might be expected. A presumption from Experiment 1 was that naming latency, unlike lexical decision latency, did not distinguish CA− from CA+ because (a) consistency was confounded with assimilation, and (b) naming is relatively less sensitive to differences in strength of consistency than lexical decision. The irrelevance of consistency to the VA− vs VA+ contrast suggests that if (a) was an important factor, then naming latency might distinguish the two harmony forms. Tasks aside, however, the simplest outcome consonant with the hypothesis that systematic phonological constraints affect visual word recognition is that both vowel harmony differences and consonant assimilation differences should be manifest as performance differences.

Method

Participants

Eighty undergraduates at Gyeongsang National University in Korea participated in partial fulfillment of a course requirement. They were assigned to the naming or lexical decision groups according to their appearance at the laboratory. None had participated in Experiment 1.

Stimuli

A total of 48 words were chosen, with 12 in each Vowel Assimilation (VA+ vs VA−) × Consonant Assimilation (CA+ vs CA−) cell. Familiarity was determined by a different group of 50 participants, who rated a much larger set of words from 1 (not very familiar) to 7 (very familiar). Mid-familiarity words were chosen, defined by ratings between 3 and 5. All words were composed of two syllables with each syllable composed of consonant–vowel–consonant.

Stimuli were evaluated further with respect to neighborhood size. So called, harmony neighborhood was estimated by a different group of 300 participants who were asked to list unique two-syllable words that could be constructed by combining other syllable blocks with either the first or second syllable block of the target stimuli. The words in a harmony neighborhood shared the same vowel relation as the target item. The number of neighbors did not differ as a function of harmony, $F(1,44) = 2.23$, $MSE = 31.69, p > .10$, nor did familiarity interact with harmony, $F < 1$.[3]

A corresponding set of 48 nonwords was created by changing letter features of a different set of words that satisfied the divisions according to presence or absence

[3] In respect to these results, it should be underscored that the measures of familiarity and neighborhood derived from the participants' population were shown in Experiment 1 to be commensurate with the measures of frequency and neighborhood derived from the KAIST database.

Table 3 Mean latency (RT) and percent error (%E) for word stimuli as a function of vowel assimilation (VA), consonant assimilation (CA) and task, in Experiment 2

VA	Task							
	Naming				Lexical decision			
	CA−		CA+		CA−		CA+	
	RT	%E	RT	%E	RT	%E	RT	%E
−	715	0.6	706	0	680	5.6	692	6.1
+	692	0.6	685	1.3	679	5.0	656	4.0

Table 4 Mean latency (RT) and percent error (%E) for nonword stimuli as a function of vowel assimilation (VA), consonant assimilation (CA) and task in Experiment 2

VA	Task							
	Naming				Lexical decision			
	CA−		CA+		CA−		CA+	
	RT	%E	RT	%E	RT	%E	RT	%E
−	721	7.5	732	7.5	741	3.3	759	3.3
+	750	11.7	746	10.0	761	4.2	762	4.2

of vowel assimilation and consonant assimilation. Given that both vowel and consonant assimilation were being controlled, restrictions on the creation of nonwords were more severe than in Experiment 1. In particular, a set of source words was chosen with the desired vowel and consonant status. Preserving vowel harmony status required that consonants, not vowels, be changed. A change in one consonant of a word typically resulted in another word. Consequently, the non-words were created by a change of at least two consonants. If possible, those changes were in the initial and final consonants of the words. If either was at the syllable boundary, then the change also had to preserve the appropriate consonant assimilation category. Importantly, over these changes the two syllables composing a nonword were legitimate monosyllabic words. In the neighborhood analysis of nonwords, neither the main effects, $Fs < 1$, nor the interaction, $F(1,44) = 2.52, MSE = 2.52, p > .10$, was significant. The average number of neighbors was below .50.

Procedure

All procedures were the same as in Experiment 1.

Results

Mean latencies and percent error on words and nonwords are provided, respectively, in Tables 3, 4. ANOVA on the mean response latencies was conducted with task (naming or lexical decision) as a between subjects variable, and CA (+ or −) and VA (+ or −) as within subjects variables.

Word Analysis

The primary expectation was that mean latency and/or mean error would differ across harmony forms (VA+, VA−) and across consonant assimilation forms (CA+, CA−).

The effect of VA, $F_1(1,78) = 39.02$, $MSE = 820.67$, $p < .0001$, $F_2(1,44) = 7.62$, $MSE = 1119.16$, $p < .01$, showed that responses to VA+ words were faster (678 ms) than responses to VA− words (699 ms). For CA, responses to CA− words were significantly slower (692 ms) than responses to CA+ words (685 ms) but only in the subjects analysis, $F_1(1,78) = 3.99$, $MSE = 979.93$, $p < .05$, $F_2 < 1$. Neither a VA effect nor a CA effect was evident in the error data (all Fs < 1).

The secondary expectation was that the effects of the two forms of assimilation would be differentially dependent on task. The Task × CA × VA interaction in the latency data was significant by subjects, $F_1(1,78) = 10.07$, $MSE = 716.34$, $p < .002$, and almost significant by items, $F_2(1,44) = 3.65$, $MSE = 530.46$, $p < .065$. In the present experiment the items composing VA+ and VA− and the items composing CA+ and CA− were matched on number of syllables, familiarity, and number of neighbors. Under these restrictions the item variance, at least within an assimilation category, was controlled experimentally with a possible concomitant reduction in the bias in F_1 (Raaijmakers et al., 1999). Accordingly, simple effects tests were restricted to subjects as the error term ($df = 1, 39$, $p < .0001$). These indicated that VA− produced slower naming than VA+ for both CA+ and CA− words ($F_1 = 14.47$ and $F_1 = 16.34$, respectively). For lexical decision, in contrast, simple effects indicated that VA- produced slower responses than VA+ only for CA+ words ($F_1 = 29.02$ vs $F_1 < 1$). The effect of CA was limited to lexical decision and, further, limited to VA+ words ($F_1 = 13.28$, $p < .001$).

Nonword Analysis

The effect of VA, $F_1(1,78) = 12.28$, $MSE = 1753.21$, $p < .001$, $F_2(1,44) = 4.57$, $MSE = 1317.25$, $p < .05$, showed that responses to VA+ non-words were slower (755 ms) than responses to VA− nonwords (738 ms). CA was not significant, Fs < 1. The CA × VA interaction was significant by subjects, $F_1(1,78) = 4.13$, $MSE = 1232.73$, $p < .05$, but not by items, $F < 1$. Simple effects tests as above showed that VA was significant for CA− nonwords, $F = 6.73$, $p < .02$. No other effects or interactions were significant by subjects, $F < 1$. The absence of an interaction between task and VA indicates that VA+ prolonged both naming and lexical decision times relative to VA−. In the error analysis, task was significant by both subjects and items: $F_1(1,78) = 18.16$, $MSE = 2.12$, $p < .0001$, $F_2(1,44) = 34.44$, $MSE = 3.46$, $p < .0001$.

Discussion

The VA+ and VA− sets of Korean disyllabic words and nonwords in the present experiment were equated for mean familiarity and neighborhood size. Unlike the CA words, VA+ and VA− did not differ in spelling-to-pronunciation consistency. The only nominal difference between them was in respect to whether or not the vowels in the component syllables were harmonious. Consequently, the visual processing of members of the two sets should differ only if participants employed phonological representations that incorporated the systematic phonological properties of spoken Korean words. That such a difference was observed in the present experiment—responses to harmonious stimuli (VA+) and disharmonious stimuli (VA−) were not identical—points to an influence of systematic phonology on visual word recognition.

The latter conclusion follows also from the present CA results. As in Experiment 1, lexical decisions were slower for CA− words than for CA+ words. In respect to the apparently diminished CA effect in the present experiment, it is important to note that the stimuli in Experiment 1 were mostly VA+. Considering only the VA+ word stimuli in the present experiment, CA– words were slower by 23 ms in lexical decision and slower by 7 ms in naming. This contrast compares favorably with that observed in Experiment 1: CA– words were 34 ms slower in lexical decision and 3 ms faster in naming.

For the VA stimuli, the patterning of the word and nonword data presents a special problem. Whereas VA+ words were responded to more quickly in the two tasks, VA+ nonwords were responded to more slowly. The implication of this pattern from the perspective of lexical decision is that the harmonious letter strings were more word-like than the disharmonious letter strings. The VA+ letter strings were easier to accept as words and harder to reject as nonwords. The implication of "more word-like" does not, however, generalize easily to naming. There is no straightforward reason that naming should be faster for words that are more word-like and yet be slower for nonwords that are more word-like. We considered whether a possible source of the slower naming of VA+ nonwords was due to an inadvertent consequence of the process for creating nonwords (see "Method"). Perhaps the initial syllables of the generated VA+ non-words were less common. Using the KAIST data base, the frequencies of the monosyllabic words that constituted the first syllables in the nonwords were determined and entered into an ANOVA with factors of VA and CA. The interaction and main effects were not significant (all Fs < 1). The absence of a difference between harmonious and disharmonious nonwords indicates that VA+ nonwords were not named more slowly than VA– nonwords because of less frequent initial syllables.

The results for vowel harmony have some bearing on the hypothesis that the phonology mediating visual word recognition might be gestural (Lukatela, Eaton, Sabadini, & Turvey, 2004). In gestural phonology a word's representation comprises dynamical systems (functional synergies) and corresponding phase relations that incorporate information about the temporal coordination of consonant and vowel gestures (Browman, & Goldstein, 1995, Gafos, 2002, Saltzman, & Munhall, 1989). The constellation of gestures defining a word captures both the properties unique to a word and the properties the word shares with many other words (the systematic phonology). In gestural phonology, a word's representation is close to its pronunciation and to its corresponding acoustic form. The idiosyncratic properties of a word and the systematic properties of a word (such as vowel harmony) are not held separate from the word but are part and parcel of its unitary representation. Accordingly, a tentative expectation from gestural phonology is that VA+ stimuli with their "compatible gestures" entail "faster assembly" of articulation. Whereas the naming of VA+ words was congruent with this expectation, the naming of VA+ nonwords was incongruent.

General Discussion

The present research was directed at the form of the phonology that mediates visual word recognition. The research addressed the question of whether this mediating phonological code reflected systematic phonology—the constraints responsible for determining the pronunciation details of classes of words. The results of Experiments 1 and 2 revealed effects of systematic phonological differences in the visual processing of word and nonword stimuli by adult readers. The results are consistent with the hypothesis investigated previously in Hebrew by Berent et al. (2001): Phonological competence, in addition to letter–phoneme correspondences, is integral to fluent visual word recognition.

In the two experiments, constraints on consonants and vowels applicable to spoken disyllabic Korean words and nonwords affected visual word recognition and might have done so in ways consistent with the functional distinction between these constraints. Harmonized disyllabic words (VA+) were responded to more quickly than non-harmonized disyllabic words (VA−) and disyllabic words with letters abiding consonant assimilation (CA+) were responded to more quickly than disyllabic words with letters not abiding consonant assimilation (CA−). The VA effect was task-independent but the CA effect was more pronounced in lexical decision than naming, an outcome that may be due in part—as discussed in Experiment 1—to the systematic association of CA manipulations with the strength of spelling-to-pronunciation consistency. For non-words, there was no CA effect but there was a pronounced VA effect that was again task independent.

In principle, the influence of systematic phonology on visual word recognition suggested by the present experiments is consonant with the *phonological coherence hypothesis* and the *universal phonological principle* identified in the introduction. At the same time the present results are potential spurs for elaborating the coherence hypothesis and universal principle in that the phonology in question is not of the kind that motivated the hypothesis and principle. Arguably, one might expect the eventual explanation of visual word identification to be expressed in terms of both decoding skills and phonological competence (Berent et al., 2001, Liberman, & Liberman, 1990, Perfetti, 1992).

Whatever the theoretical construal of the present results, it should be evident that further study of the constraints of systematic phonology on visual word recognition is warranted, both in the writing systems investigated so far (those of Hebrew and Korean) and the writing systems of other languages. The phonological components of current models of visual word recognition tend to be developed with little consideration of formal phonological theory. The promise of extending the present line of research is not only a potentially better grounding for modeling efforts but also for a deeper understanding of reading's relation to speech.

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