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Phonological Inference and Word Recognition: Evidence from Korean

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PHONOLOGICAL INFERENCE IN WORD RECOGNITION: EVIDENCE FROM KOREAN OBSTRUENT NASALIZATION

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ABSTRACT

Gaskell and Marslen-Wilson (1996) use data from cross-modal priming to show that word recognition involves phonological inference: listeners more readily recognize a word that is changed from its canonical form if that change is conditioned by a phonological process. Subsequent research has questioned whether word recognition does in fact involve phonological inference, based on evidence that perceptual compensation for assimilation can involve universal, rather than language-specific mechanisms (Gow 2003) and on evidence that changes are accepted even outside of the context in which they are phonologically conditioned (Wheeldon and Waksler 2004). We present new evidence for phonological inference based on a cross-modal priming study with Korean listeners, which shows that they accept an obstruent-to-nasal change (e.g. [sok] as [soŋ] 'inner part') only when that change occurs in the context of a following nasal (e.g. [soŋmaɨm] 'innermost feelings'), the environment in which it occurs in Korean phonology. We propose that listeners perform a phonological viability check, in which lexical hypotheses are submitted to the phonological grammar to determine if they are viable given the phonological context. We further suggest that a probabilistic viability check can explain apparent differences in robustness of the inference effect across different types of phonological process.

INTRODUCTION

Gaskell and Marslen-Wilson (1996) (henceforth GM-W) present results from cross-modal priming experiments showing that English listeners accurately recognize a word whose final consonant's place of articulation has been altered to have same place of articulation as a following consonant. For example, [grim], with a final labial replacing the coronal of [grin], is recognized as a variant of *green* when it is followed by another labial (e.g. in [grimbin] *green bean*). GM-W's results indicate that this effect is contingent on phonological context; [grim] would be less likely to be recognized as *green* when a non-labial consonant follows (e.g. [grimgræs] for *green grass*). Since the conditions under which changes in place of articulation are tolerated in word recognition correspond to the conditions under which the phonological process of place assimilation occurs in English (coronals assimilate to following non-coronals), GM-W take these results as evidence that listeners perform *phonological inference* in word recognition. That is, the word recognition process involves a calculation of whether a discrepancy from the canonical form of a word is due to the application of a phonological change.

Subsequent research has questioned whether word recognition involves phonological inference. Gow (2003) argues that listeners cope with this sort of variation in the form of words with universal (non-language-specific) perceptual mechanisms. Under Gow's feature parsing theory, the listener attributes the presence of acoustic cues to labiality in [grim] to the presence of the following labial consonant in [grimbin]. Gow supports this account by showing that partially assimilated segments are interpreted on the basis of the following consonant: a consonant intermediate between [n] and [m], which can be interpreted as either [n] or [m] in isolation, is perceived as [m] before a word like *tables* because the coronal cues are attributed to the [t], and as [n] before a word like *buns* whose initial consonant provides the source of labiality. The interpretation of the ambiguous consonant as [m] before *tables* cannot be the undoing of a phonological process, since English does not have labial-to-coronal assimilation (see further Gow and Im 2004 and Mitterer *et al.* 2006ab).

A different challenge is provided by Wheeldon and Waksler (2004), who argue for a phonological underspecification account of listeners' tolerance for variation in the phonetic shape of words (following Lahiri and Marslen-Wilson 1991). In this view, [grimbin] is acceptable because the lexical representation of the final coronal in *green* lacks a specification for place of articulation (i.e. /griN/, where N is a nasal unspecified for place). They support this account with results from a new version of GM-W's priming study, which replicated G-MW's finding that tolerance for place changes is limited to word-final coronals, but failed to replicate the context effect: their results indicate that listeners would equally accept [grim] as *green* in both [grimgræs] and [grimbin]. They argue that these findings support an analysis in which English (word-final) coronals are underspecified for place, since under this account the acceptability of [grim] for /griN/ does not depend on whether there is a following labial (see also Lahiri and Reetz 2002).

There has also been research subsequent to GM-W that favors the phonological inference account of their findings (see Gaskell and Snoeren in press for a recent summary). For example, Darcy *et al*. (2007) tested subjects whose native language phonologies contain different processes: English subjects whose phonology includes the above-mentioned place assimilation, and French subjects whose phonology includes voicing assimilation, in which an obstruent takes on the voicing specification of the following consonant (e.g. [rob] *robe* vs. [ropsæl] *robe sale*). French lacks place assimilation, and English lacks voicing assimilation. The results from a word-spotting task provide evidence that tolerance for changes in the shape of words is language-specific and sensitive to phonological context (though they do note that there is also some evidence for language-independent compensation strategies). Language specificity is not expected under Gow's perceptual compensation account, and context-sensitivity is not expected under the "pure" version of the underspecification account that Wheeldon and Waksler (2004) adopt.

Because the evidence for context- and language-specificity is inconsistent across studies, and because Darcy *et al*. used a relatively off-line word-spotting task, the role of phonological inference in word recognition remains to be firmly established. In this paper, we discuss further evidence of phonological inference involving a phonological process in Korean. In Korean obstruent nasalization, obstruents become nasals in the presence of a following nasal. Examples of this process are provided in (1). The underlying forms in slashes show the forms as they would be produced in isolation (e.g. [pap] 'rice'). The forms in phonetic square brackets show how the words are produced when concatenated into a compound: the word final obstruents are produced as nasals due to the presence of the following word-initial nasals (e.g. [pam]). Note that if they do not undergo the independent process of place assimilation (see section 2 below), the nasal-assimilated segments retain their original place of articulation, as shown especially in (1d).

(1)	a. /pap + mul/	[pammul]	'rice water'
	b. /pat^h + noŋsa/	[pannoŋsa]	'field farming'
	c. /os + noŋ/	[onnoŋ]	'a clothes chest'
	d. /kuk + mul/	[kuŋmul]	'broth'

In an earlier study reported in part in Lee (2005ab), we used a word-spotting methodology adapted from Darcy *et al*. (2007), and found that Korean speakers, but not English speakers, accept the realization of an obstruent as a nasal in the context of a following nasal, but not in the context of other following consonants. We discuss the results of that study in the next section, "Word Spotting and Korean Nasalization".

While these results do suggest that phonological inference is at work in Korean speakers' recognition of word-final obstruent-nasal alternations, this interpretation is subject to the same caveat as the similar interpretation of Darcy et al.'s results from English and French. Word spotting, especially the variant we employed, is a relatively off-line task, and it could be that listeners are able to conduct phonological inference under those conditions, but do not employ it in on-line speech recognition. We therefore conducted a cross-modal priming study using a methodology adapted from GM-W. Again, we found that Korean subjects recognize words whose final obstruents are realized as nasals if and only if the following nasal context is present. These new results are presented in the section entitled "Cross-modal priming and Korean nasalization".

Given what seems to be incontrovertible evidence of phonological inference in word recognition, an adequate model of speech recognition must include a mechanism by which listeners assess the phonological viability of lexical hypotheses. In the "Discussion" section, we propose that listeners determine the probability of hypothesized lexical representations given the perceived phonological string by submitting them to their phonological grammar. We formalize this phonological viability check in terms of Optimality Theory (OT: Prince and Smolensky 1993/2004), and show how a probabilistic version of this theory may explain the apparently greater robustness of phonological inference in the case of Korean obstruent nasalization relative to English place assimilation.

We conclude that word recognition involves both perceptual compensation of the type documented by Gow (2003) and others, as well as a mechanism of phonological inference as proposed in GM-W.

WORD-SPOTTING AND KOREAN NASALIZATION

In our earlier study, we investigated not only obstruent nasalization, but also place assimilation. As in English, in Korean a consonant often takes on the place of articulation of the immediately following one. Also as in English, coronal consonants assimilate to following velars (2a,b) and labials (2c,d). Korean, however, has an assimilation pattern missing from English: labials assimilate to following velars (2e,f).[1]

(2)	a. /pat + ko/	[pakko]	‘receive and’
	b. /han + kaŋ/	[haŋgaŋ]	‘the Han river’
	c. /kot + palo/	[koppalo]	‘straight’
	d. /han + pən/	[hambən]	‘once’
	e. /əp+ko/	[əkko]	‘bear on the back + conj.’
	f. /namkɨk/	[naŋgɨk]	‘the South Pole’

Our experiment tested nine types of assimilation process, shown schematically in (3), where T = coronal, K = velar, P = labial, and N = nasal. The rules in (3a-c) schematize the Korean place assimilation processes in (2). Those in (3d-f) correspond to place assimilation processes that do not occur in Korean. The rules in (3g-j) correspond to the obstruent nasalization patterns shown in (1).

[1] In these and further examples there are also instances of other phonological processes that we will not discuss. Korean has coda neutralization: obstruents in coda position are produced as unreleased lax stops (these can be underlyingly plain (e.g. /p/), aspirated (/p^h/) or tensed (/p’/). Further, obstruents are realized as voiced between voiced sounds.

(3)	a. T → K / _ K	d. K → T / _ T	g. P → m / __ N
	b. T → P / _ P	e. P → T / _ T	h. T → n / __ N
	c. P → K / _ K	f. K → P / _ P	i. K → ŋ / __ N

We tested for phonological inference using an adapted version of Darcy *et al.*'s (2007) word-spotting methodology. The environment for the assimilation process was provided by compound word formation (as opposed to the sentential contexts used in Darcy *et al*. 2007). For each of the cases in (3) there were three conditions, illustrated in (4) for T → K / _ K using English examples.

(4)	*No Change*	*Change Viable*	*Change Unviable*
	ca[t] tail	ca[k] claw	ca[k] scratch

The No Change condition contained the canonical form of the word in first position of the compound: in this case [kæt] for *cat*. In Change Viable, the modified form appears in the context in which it is conditioned by the phonological process: here [kæk] appears before the [k]-initial *claw*. Finally, Change Unviable contains the modified form in a context in which the change is not conditioned, for instance [kæk] before the coronal [s] of *scratch*.

For each of the 9 processes, we chose 5 real words as the first members of the compounds, matched in frequency across processes. We also created 5 nonce words for each of the processes. We then created changed versions of each of these words (e.g. ca[k] for ca[t]). Both the real and nonce words were each paired with three real words to form the three types of compounds illustrated in (4). We created the compounds by splicing the first and second words together, each recorded separately in neutral contexts. The modified forms of words thus had categorically changed consonants.

The 270 compounds thus created were each embedded in an experimental item, in which the unmodified form was first presented in isolation, followed by a 1.5 second pause, and then the compound. These were presented to subjects in random order. They were asked if the unmodified form and the first member of the compound matched, and circled the Korean equivalent of 'same' or 'different' on an answer sheet.

The results from 41 Korean-speaking college-aged subjects, tested at Hoseo University in Korea, are shown in Table 1, where NC = No Change, CV = Change Viable, and CU = Change Unviable. The results are grouped into the three types of pattern discussed above: obstruent nasalization (‘Nasalization’), place assimilation attested in Korean (‘Place-Korean’), and place assimilation unattested in Korean (‘Place-Non-Korean’). The error bars display 95% confidence intervals.

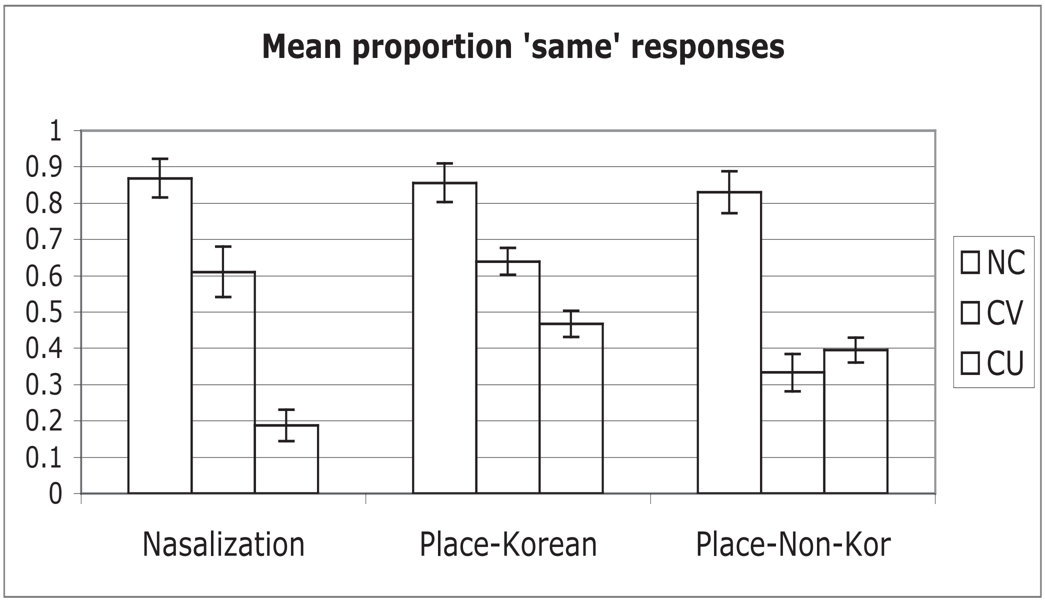

Table 1 Word spotting by Korean subjects

The comparison of interest is between the rightmost pair of bars in each group. Phonological inference predicts that the proportion of ‘same’ responses should be higher in the viable context (the middle bar, CV) than in the unviable one (CU). For obstruent nasalization, this is clearly the case (μ(CV) = 0.61, μ(CU) = 0.19; paired t-test $t(40) = -11.5$, $p < 0.001$). There is also a significantly greater proportion of ‘same’ responses for CV than CU in Korean place assimilation, though the difference is smaller (μ(CV) = 0.64, μ(CU) = 0.47; paired t-test $t(40) = -7.1$, $p < 0.001$). For the non-Korean place assimilation patterns, there is no evidence of phonological inference.

To further test the language-specificity of this result, we created a version of the experiment using English materials, but with same set of assimilation processes, and tested both Korean and English listeners. For obstruent nasalization (e.g. ‘pop music’ as ‘po[m] music’), the

41 Korean subjects continued to show a higher proportion of 'same' responses in CV ($\mu = 0.38$, S.D. = 0.22) than CU ($\mu = 0.21$, S.D. = 0.18). For the present paper, we tested a comparison group of 13 college-aged English subjects at the University of Massachusetts, Amherst (Lee 2005a reports similar results from 8 English speakers tested in Korea). The English speakers showed no evidence of performing phonological inference for obstruent nasalization; they gave a slightly higher proportion of 'same' responses in CU ($\mu = 0.28$, SD = 0.21) than CV ($\mu = 0.26$, SD = 0.20). A one-tailed t-test shows that the difference between CV and CU was significantly different between English and Korean subjects ($t(52) = 3.868$, $p < 0.01$). Out of the 9 assimilation conditions, the only ones in which the English speakers gave a higher proportion of 'same' responses to CV than CU was for the ones that correspond to English assimilation processes (T → K / _ K, μ(CV) = 0.77 (SD 0.19), μ(CU) = 0.53 (SD 0.21); T → P / _ P , μ(CV) = 0.62 (SD 0.19), μ(CU) = 0.55 (SD 0.21)).

As we have already mentioned, while these results are suggestive, they do not necessarily imply that speakers perform phonological inference in speech recognition. In this off-line task, the subjects could have assessed how they would pronounce the isolated word in the given compound context by performing a sort of virtual phonological production. To gather better evidence of phonological inference in word recognition, we therefore conducted a cross-modal priming task as in GM-W, which we describe in the next section. We decided to focus on obstruent nasalization because the CV-CU difference was so robust in the word-spotting task, and because we hypothesized that the mixed results on place assimilation in earlier priming studies (e.g. GM-W *vs*. Wheeldon and Waksler 2004) might be due to some factor specific to that process (see section 4.1 below for further discussion).

CROSS-MODAL PRIMING AND KOREAN NASALIZATION

Method

In GM-W's cross-modal priming methodology, the target word is presented visually in orthographic form, and subjects are asked to make a lexical decision (word/non-word). Preceding the target is an aurally presented sentence, which may contain as a prime the same word as the target. The priming effect is measured by comparing reaction times for the items with identity primes to control items that lack primes. To measure phonological inference, the degree of priming is compared between items that contain primes that are manipulated in the same way as the word-spotting study discussed above: those in which the prime is in its canonical form (NC/No Change), those in which the word-final consonant has been changed appropriately for the following phonological context (CV/Change Viable) and those in which the change occurs with an inappropriate following context (CU/Change Unviable). Phonological inference predicts faster reaction times in the CV condition than in CU, since the priming effect should be stronger in CV. Unlike word-spotting, this method is an on-line measure of phonological inference; inference may affect priming, but the subjects respond only to the target. This method is also especially appropriate for measuring phonological inference in word recognition because cross-modal repetition priming has proved to be sensitive to the activation of lexical representation, but not to lower level form-based affinities (GM-W).

Materials and design

A total of ninety sentences were constructed for 30 test words. The sentences were manipulated with regard to three factors: the presence or absence of a phonological change in the word-final consonant of the prime word, the phonological viability of the following context, and the prime-target relationship. Among the 30 test words, 14 were monosyllabic and 16 were bisyllabic. 10 test words had a coronal final consonant, another 10 had a labial final consonant, and the other 10 had a velar final consonant. The 30 test words each occurred in 3 different contexts: no-change context (30 sentences), phonologically viable context (30 sentences) and phonologically unviable context (30 sentences). All of the test words were nouns, and the following context was provided by the first consonant of a second noun. These noun pairs formed noun-noun compounds. The compounds were embedded in a sentential context. The sentences consisted of 5 words on average (range of 4-7). Importantly, the four sentences created for each test word had a common beginning and any syntactic or semantic differences between condition sets were minimized. This avoided potential priming of the target that might be caused by the sentential context itself. Examples of each sentence type are shown in Table 2.

As mentioned above, the final consonant of the prime word was either a nasal or an obstruent. In most cases, the nasal-feature change of the word-final consonant of the prime word resulted in a nonword. Because it was not possible to create enough compound words in which the change always resulted in a non-word (especially with monosyllables), in a small number of cases we used feature changes that created real words. These were onomatopoeic (e.g., /t’əŋ/,

/tʰəŋ/), rarely used in present-day Korean (e.g., /pin/), or infrequent affixes (e.g., /on/, /min/). Moreover, all the resultant noun compounds were always nonwords.

Change Viable	Mono-syllable	/sok + maɨm/ [soŋmaɨm] ‘one’s innermost feelings’ Nay chinkunun machimnae sokmaumul tulenaeessta. ‘My friend finally revealed his innermost feelings.’
	Bi-syllable	/totuk + nom/ [toduŋnom] ‘a thief guy (a thief)’ Yengcinika yongkamhagey totuknomul capassta. ‘Yengcin caught a thief bravely.’
Change Unviable	Mono-syllable	/sok + pimil/ [soŋbimil] ‘one’s innermost secret’ Nay chinkunun machimnae sokpimilul thelenoassta. ‘My friend finally disclosed his innermost secret.’
	Bi-syllable	/totuk + ʧam/ [toduŋʤam] ‘a thief’ sleep (a light sleep)’ Yengcinika nammollae totukcamul cassta. ‘Yengcin slept a light sleep without anyone’s notice.’
No Change	Mono-syllable	/sok + t’ɨs/ [sok t’ɨt] ‘inner meaning’ Nay chinkunun machimnae phyenciuy sokttusul ihaehaessta. ‘My friend finally understood the inner meaning of the letter.’
	Bi-syllable	/totuk + ʧaŋka/ [todukʧaŋga] ‘a thief’ marriage (a secret marriage)’ Yengcinika somunepsi totukcangkalul tulessta. ‘Yengcin married secretly without fanfare.’

Table 2 Sample prime words in the three phonological contexts. Korean sentences are transcribed in Yale Romanization.

The test sentences were presented with visual targets that matched the prime words; the words in Hangul orthography. In addition, there were 30 control sentences in which the prime words occurred with non-matching visual targets, orthographic forms of words that were phonologically and semantically unrelated. These were used as a baseline for evaluating priming effects. Like the test items, all of the control items were obstruent-final in their isolation form. Half of them were presented with the final consonant changed to a nasal. All primes in the control sentences were also nouns, matched with the test items for the number of syllables and word frequency (see the Appendix). Moreover, they occurred in the same sentential context as the test prime words.

Pretest

A pretest was administered to assure that the speech tokens embedded in the priming task had the correct phonetic form. That is, that tokens used in the change conditions could be identified as having a nasal, whereas those in the no change condition could be identified as having an obstruent. A forced-choice task was conducted to inspect whether participants could hear the intended phonetic forms (i.e., the nasalized and oral phonetic forms of the word-final consonant of the prime word), as in GM-W. In the pretest, the sentences were auditorily presented up to the offset of the prime word in order to ensure that the following contexts of the prime word would not bias participants' responses.

Participants

Thirty-six freshmen recruited from the department of English language and literature at Hoseo University took the pretest for course credit. All were native Korean speakers.

Procedure

In the pretest, the 120 sentences were split into 3 blocks, each including 40 sentences. Each of the 30 test words occurred only once within each block, making a total of 90 setences. The 30 control sentences made up the rest of the items. In addition, there were 6 practice sentences. Participants were asked to choose between the unchanged and the changed form of the prime word in a forced-choice test. The participants were tested in a sound-attenuated room during a regular class hour. They were provided with answer sheets on which two variants of the prime word were presented; the changed form of the prime word and the unchanged form of the prime. The participants heard the sentences, which consisted of only left context and the prime word, over headphones. Then they had 3 seconds to mark the word that they heard on the answer sheet. Before the pretest, the participants completed 6 practice sentences. The test lasted around 12 minutes.

Results

In the pretest, if a participant chose the intended pronunciation of the word-final consonant, it was regarded as a correct response. All participants' responses for each test item in each condition were more than 90% correct except only a few items. Unlike other test items, however, one item in the unviable context showed a high error rate (22.5%) due to its poor quality and thus it was replaced by another stimulus. The mean percentage correct and the standard error for the participants' responses of test items in each condition are shown in Table 3.

Final consonant	Condition	Mean (SE)
Nasal	Change Viable	97.4 (.518)
	Change Unviable	98.9 (.518)
	Control	98.3 (.518)
Obstruent	No Change	98.9 (.518)
	Control	99 (.518)

Table 3 Mean percentage correct and standard error in the pretest

As can be seen, the mean percentage correct in each context was around 98% and the differences between conditions were very small. An ANOVA was conducted with the variables of phonological change and context. There were no main effects of either variable (change: $F<1$ ns, context: $F=1.5$, ns). This indicates that word-final nasal and obstruent consonants of the prime words in each context were unambiguously perceived and that any subsequent results can be interpreted without a confound in terms of the phonetic quality of the test items.

Main experiment

The main experiment employed cross-modal repetition priming, as in GM-W and Wheeldon and Waksler (2004). The pretested sentences were used, but were presented in their full form in the main experiment to investigate whether the following phonological context affects a visual lexical-decision process.

Materials and design

The same 120 experimental sentences as in the pretest were used; 30 sentences for the No Change condition, 30 for the Change Viable condition, 30 for the Change Unviable condition, and 30 for the Control condition. In addition, 90 filler sentences with nonword targets were included. Similar to Wheeldon and Waksler (2004), two thirds of the filler sentences (60 sentences) had phonologically related prime words and one third (30 sentences) had phonologically unrelated prime words. Half of the nonword primes had a changed final segment (i.e., a nasal consonant) in both the prime and target related and unrelated sentences. The filler sentences were interspersed with the test sentences in order to reduce a possible prime-target relationship. The filler sentences were matched with the test sentences with respect to sentence length. In addition, there were 8 practice sentences.

Participants

Thirty-five participants were recruited from several universities in the Seoul metropolitan area. All of them were undergraduate students, except four graduate students, and ages ranged from 18 to 29 years. None of them had participated in the pretest.

Procedure

Each participant was tested individually or in groups of two. The experiment was run using E-prime software. Eight practice sentences were first presented and then followed by three blocks of 70 sentences. Accordingly, each participant was tested with a total of 218 sentences. Each test word appeared in all three blocks but in different context within each block. For example, the unchanged form [sok] of the target word *sok* ‘the inner part’ occurred in no-change context in the second block, while its changed form [soŋ] appeared in phonologically viable context in the third block. The changed [soŋ] also occurred in phonologically unviable context in the first block. In addition, the control word *ak* ‘a vice’, which is phonologically and semantically unrelated to the target word *sok*, appeared in the first block. There were breaks between blocks and the order of items and blocks was randomized across participants. Each sentence was presented after a warning beep and a short interval. At the offset of the prime word, the target word appeared for 3 seconds (or until a response is being made) on the monitor located in front of the participant. The participant was asked to press the *yes* button positioned by a participant’s right hand if the target was a word. If the target was not a word, the participant was instructed to press the *no* button. The reaction time was measured from the offset of the prime word, as in GM-W. Participants had 3 seconds for a lexical-decision response and the procedure was repeated after a 2-second inter-trial interval.

Results

None of the participants showed error rates higher than 8.4% except one participant (15%). However, her data were not excluded from analysis, as her error rate was rather low compared to that of previous studies (e.g., data with error rates over 20% were excluded in GM-W). As in Wheeldon and Waksler (2004), correct individual item reaction times that were either under 300ms or over 3000ms were excluded, which led to the exclusion of only one participant's response to one item in the subsequent analysis. The mean reaction times and error rates are summarized in Table 4.

Condition	*RT (% error)*	*Priming*
Change Viable	636 (2.9)	115 (2.8)
Change Unviable	672 (4.1)	79 (1.6)
No Change	631 (1.6)	120 (4.1)
Control	751 (5.7)	

Table 4 Mean reaction times (in milliseconds) and percentage error rates (in parentheses) for the Main Experiment

In order to examine whether there is any difference between phonologically changed and unchanged control stimuli, a paired-samples *t*-test was run on the control data. The difference in reaction times (RTs) between phonologically changed and unchanged stimuli was not significant ($t(34) = -.421$, $p > .05$), but that of percentage error rates was significant ($t(34) = 5.389$, $p < .001$). This was because changed stimuli showed higher error rates compared to unchanged stimuli (9% vs. 2.5%). However, given the overall low percentage error rates across contexts, the priming effects given in Table 4 (and also in all subsequent analyses) are calculated based on the mean of the phonologically changed and unchanged control stimuli, similar to Wheeldon and Waksler (2004).

The means in Table 4 indicate that the reaction times of the Change Viable and No Change conditions were the fastest, followed by Change Unviable, and then by the Control items. We conducted a repeated measures ANOVA on mean RTs, with these four conditions as a variable. There was a significant effect of condition, $F(3, 102) = 47.033$, $p < 0.0001$. Tukey pair-wise comparisons revealed that RTs in the primed contexts were all significantly faster than in the control context (all $p < 0.0001$). Importantly, the differences in RTs between Change Viable and Change Unviable and between the No Change and Change Unviable were significant ($p < 0.05$, $p < 0.01$, respectively). Yet, the difference between the No Change and Change Viable conditions was not significant ($p > 0.05$). These results show participants' tolerance of mismatch in lexical access in the viable context, similar to the no-change context, but not in the unviable context, thus supporting the prediction of the phonological inference account of word recognition. Similarly, percentage error rates showed a significant effect of condition, $F(3, 102)=8.428$, $p < 0.0001$, as the control condition yielded more errors than all the target-related prime contexts. Post hoc tests using the Tukey indicated that the differences in error rates between the following pairs were significant; No Change and Change Unviable ($p < 0.05$), the No Change and Control contexts ($p < 0.0001$), and Viable and Control contexts ($p < 0.01$).

Moreover, further analysis was performed on the priming effects themselves (that is, Control mean minus target-related prime context means), as in Wheeldon and Waksler (2004). This is for a direct comparison of the amount of priming gained in the primed contexts. A repeated measures ANOVA was conducted on the priming data (Table 4) with the variable context. Both analyses of the RTs and the error rates revealed a significant effect of context; reaction times: $F(2, 68)=9.623$, $p<.0001$, error rates: $F(2, 68)=6.451$, $p<.01$. Specifically, Tukey pair-wise comparisons yielded that the difference in RTs was significant not only between the No Change and Change Unviable conditions ($p<.0001$) but also between Change Viable and Change Unviable ($p=.002$). Yet, the difference between the No Change and Change Viable was not significant. As for the error rates, only the difference between No Change and Change Unviable was significant ($p = 0.002$). Thus, the results on the priming effects themselves also support the phonological inference account of word recognition, as nasals in the unviable context yielded a 36ms mismatch effect compared to those in the viable context.

In this experiment, the participants heard all the target-related primes across all contexts as well as the target-unrelated control primes. Accordingly, this might cause some residual effects on both related and unrelated primes. Thus, we performed an analysis on the data obtained from each block to examine whether there was an effect of blocks. The results indicated that neither reaction times, $F(2, 68) = 0.864$, $p > 0.05$, nor error rates, $F(2, 68) = 2.022$, $p > 0.05$, showed any effects of blocks. This suggests that there were no residual effects on the experimental stimuli, even though the participants heard all the target-related and target-unrelated prime words in the experiment.

DISCUSSION

Obstruent nasalization vs. place assimilation

Given the strong effect of phonological context that we found for the perceptual consequences of obstruent nasalization in Korean, one might wonder why the effect seems less robust for place changes, given the contradictory results between GM-W and Wheeldon and Waksler (2004), and also the differences in our Korean word-spotting results in Table 1. There are several differences between these processes that are relevant to this question, and also to the interpretation of our results.

The first is that differences in obstruent nasalization are likely perceptually more salient than differences in place of articulation, especially in preconsonantal position. Evidence for the general relative saliency of nasalization changes can be found in studies of perception in noise, such as Miller and Nicely (1955) and Cutler et al. (2004), in which consonants differing only in nasality are rarely confused in comparison with consonants differing in only in place.

Cues for place of articulation in preconsonantal position are notoriously weak, and this weakness has even been hypothesized to be the source of the assimilation process (Jun 1995, Steriade 2001). Furthermore, recent work by Key (2008) shows that English subjects are unable to discriminate coronals from labials in pre-labial position (TP vs. PP), or coronals from velars in pre-velar position (TK vs. KK) in an AX same-different task, even with a relatively short interstimulus interval (250 msec.). The weakness of the perceptual cues for place in preconsonantal position may be at least part of the explanation for the lack of a context effect in Wheeldon and Waksler (2004). In word recognition, speakers may relatively easily discount contradictory acoustic evidence if that evidence is relatively weak.

Although the acoustics of the Korean obstruent/nasal contrast has not been the focus of the same kind attention as English place of articulation, there is some indication that it is relatively easy to perceive. In particular, Kabak and Idsardi (2005) provide some evidence that it is robust even in the environment in which the process of obstruent nasalization eliminates the contrast. In an experiment that focused on another type of contrast, they included one test item that contrasted a nasal with an obstruent prenasally ([p^hakma] vs. [p^haŋma]). Even though the interstimulus interval was very long (1500 ms.), Korean subjects in an AX same-different task discriminated the pair successfully, at a rate equal to that of English subjects. We suspect that this result would generalize, based on the first author's perception of English pairs of this sort, and our informal queries of other native speakers.

The perceptual robustness of the obstruent/nasal contrast would make the change in the unviable context particularly noticeable, and contribute to a large difference between that context and the viable context. That place and nasality differ in this way is attested to in the word-spotting results from Korean in Table 1 above. The proportion of 'same' responses in the unviable context was only 0.19 for nasalization, but 0.47 for place.

Another important consequence of the robustness of this contrast is that it renders one alternative explanation for our results relatively unlikely: that Korean listeners simply do not perceive a difference between nasals and obstruents in the pre-nasal environment. A similar interpretation of some results on perceptual compensation is in fact quite plausible (see e.g. Mitterer et al. 2006b: 474). In this case, it seems more likely that Korean listeners represent the nasal as distinct from an obstruent at the pre-lexical level of processing, and use their phonological knowledge to infer that it can be derived from a lexical obstruent.

The second difference between place assimilation and obstruent nasalization is that nasalization seems to be a fully categorical neutralizing process. English place assimilation is notoriously gradient, in more than one way. First, it applies optionally, and is sensitive to rate of speech. Second, when it does apply, the outcome may be intermediate between categories, retaining a coronal tongue tip gesture along with labial or velar closure (Browman and Goldstein 1990, Nolan 1992; cf. Ellis and Hardcastle 2002). Again, the articulatory details of Korean obstruent nasalization have not (yet) been the subject of such intensive study, but all indications point to it being obligatory and category changing.

The categorical/gradient difference could affect the results of speech recognition studies in at least two ways. First, the stimuli in these studies are usually prepared with categorical changes (cf. Gow 2003). If the process at issue is in fact categorical in this way, the stimuli would be more natural than if it (sometimes) yields between category outcomes. Second, if the process applies optionally, then this could have consequences for the nature of the system of perceptual compensation that listeners develop prior to the experiment. Presumably, a system developed on the basis of experiencing consistent application of the process would be more attuned to dealing with the change. In the next section, we provide the beginnings of a formal model of this explanation.

In sum, there are several reasons why one might have picked Korean obstruent nasalization *a priori* as a better source of phonological inference effects than English place assimilation. Further, due to the perceptual saliency of the contrast, it seems likely that this is truly phonological inference, rather than a lower-level perceptual neutralization.

Toward a model of phonological viability checking

We take these results to firmly (re-)establish the role of phonological inference in word recognition. While we will not attempt to fully develop a model of phonological inference, let alone integrate one into a model of word recognition, we will here sketch what we imagine what such a model might look like. For earlier theories of phonological inference, see Gaskell *et al*. (1995) and Gaskell (2003) as well as GM-W; comparison between our model and these would be premature, since ours is relatively underdeveloped.

Models of word recognition assign probabilities to lexical candidates for the perceived acoustic signal (see Norris and McQueen in press for a recent review of competing theories, and an explicitly probabilistic proposal). Our results, and those of GM-W and Darcy *et al*. (2007), amongst others, indicate that this probability is conditioned by phonological knowledge. In particular, the degree to which a change from the canonical form of a word lowers the probability of that word depends on whether that change is phonologically conditioned.

One way to formalize phonological inference is to submit lexical hypotheses to the phonological grammar to see if they map to the perceived string: a positive outcome increases probability, and a negative one decreases it (see Moreton 2007 for an earlier proposal that makes use of phonological viability checking in perception). Here we first show how this would work in

Optimality Theory (OT: Prince and Smolensky 1993/2004), using the example of Korean obstruent nasalization (see Boersma 1999 for a different approach to word recognition in OT). We then discuss a version of this proposal that uses a stochastic version of OT that extends to the variation in English place assimilation, and to the apparent differences in the robustness of the effect of phonological inference in the two cases.

The phonological grammar in OT makes use of two kinds of constraint. *Faithfulness* constraints penalize divergences between the form of words in the lexical and surface representations. The relevant faithfulness constraint for Korean obstruent nasalization is IDENT-NASAL (McCarthy and Prince 1999), which penalizes a change from a lexical obstruent to a nasal. The other type of constraint penalizes particular structures in the surface representation. We will use the term *structural* constraint, though these are more often termed markedness constraints. The relevant structural constraint penalizes obstruent-nasal sequences (*ON). In Korean, *ON ranks above IDENT-NASAL, thus preferring the change of the obstruent to a nasal over the unchanged form. This is shown in the tableau in (5), which provides two surface candidates for the lexical input /sok+maɨm/ 'innermost feelings'. The lexical input is shown in the top leftmost cell, and the surface candidates are in the cells beneath. The violations incurred by each surface candidate are shown by asterisks in each one's row, beneath the relevant constraint. The pointing finger indicates the optimal mapping, which is chosen because it violates the lower ranked constraint (ranking is indicated by left-to-right order of constraints).

(5) *OT tableau for Korean obstruent nasalization*

/sok + maɨm/	*ON	IDENT-NASAL
☞ [soŋmaɨm]		*
sokmaɨm	*	

In contrast, outside of the context for nasalization, the candidate with no change wins, since it does not violate *ON:

(6) *No nasalization before obstruents*

/sok + pimil/	*ON	IDENT-NASAL
soŋbimil		*
☞ [sokpimil]		

To check for phonological viability in word recognition, lexical hypotheses can be submitted to the same evaluative procedure to see if the perceived string is in fact chosen as optimal. The tableau in (5) illustrates a viability check for an obstruent-nasal input-output mapping in a viable context. Here, the candidate with the nasalized final consonant is the optimal form. If this check were performed in an unviable context, the result would be as in (6): the perceived nasal would lose to the faithful mapping. If the failure of a viability check lowers the probability of a lexical hypothesis, this accounts for our experimental findings.

Somewhat more formally, we can say that given a set of lexical hypotheses, and the result of a phonological viability check on each one, which returns a score of +1 if successful, and 0 if failed, that this score can be used a weighted factor in the calculation of the probability of each hypothesis. It is also possible to incorporate a gradient, continuous version of this factor, where the phonological viability check itself returns a real valued number between 0 and 1 indicating the probability of the observed surface outcome given a lexical hypothesis. In what follows, we briefly discuss how this probabilistic viability check could be used to account for the difference between the robustness of phonological inference for English place assimilation and Korean obstruent nasalization.

Although the original version of OT produces only a single optimal form in a candidate set, several revised versions of the theory produce a distribution over candidates in order to account for phonological variation (see Anttila 2007, Coetzee and Pater to appear for overviews of this literature). We can use a probabilistic version of OT to account for the optionality of English place assimilation. Here we will make the simplifying assumption that this process involves variation between two outcomes: full assimilation and no assimilation. We adopt the probabilistic version of OT proposed by Johnson (2002) and Goldwater and Johnson (2003), in which the probability of a candidate is proportional to a numerical measure of its well-formedness. This numerical measure first multiplies each constraint violation score by the constraint's weight, and then sums the results. This weighted sum is the *harmony* of a representation in Harmonic Grammar (HG; Smolensky and Legendre 2006). In the probabilistic version of HG proposed by Johnson (2002), the candidate's probability is proportional to the exponential of its harmony.

In the tableau in (7), the constraints are AGREE-PLACE, which requires adjacent consonants to have the same place of articulation, and IDENT-COR, which requires an underlying coronal to map to a surface coronal (see Jun 1995). The constraint violations are indicated by negative integers in place of violation marks, and each constraint's weight appears in the same cell as its name. The last three columns show each candidate's harmony (H), the exponential of its harmony, and its probability.

(7) *Variable assimilation in probabilistic HG*

/grin + bin/	AGREE-PLACE 1	IDENT-COR 1	*H*	e^H	P
[grimbin]		–1	–1	0.37	0.5
[grinbin]	–1		–1	0.37	0.5

To get a non-variable outcome, the weights of conflicting constraints must be sufficiently far apart to make the probability of the observed outcome (nearly) 1. This is illustrated for Korean obstruent nasalization in (8). By increasing the scale of the difference between *ON and IDENT-NASAL, the non-asssimilated candidate can be made vanishingly improbable.

(8) *(Nearly) non-variable assimilation in probabilistic HG*

/sok + maɨm/	*ON 5	IDENT-NASAL 0.1	*H*	e^H	P
[soŋmaɨm]		-1	–0.1	0.90	> 0.99
[sokmaɨm]	-1		–5	0.01	< 0.01

We can now see how a probabilistic grammar allows a gradient version of a phonological viability check.

For variable place assimilation the viability check assigns a score of 0.5 to [grim] for /grin/ in the viable context of [bin]. This would contrast with the non-word /grim/, which would receive a score of nearly 1. It would also contrast with the score for /grin/ as [grim] in the unviable context of [græs], which would receive a score of nearly 0.

For non-variable obstruent nasalization, [soŋ] for /sok/ in the context of [maɨm] receives a score of nearly 1. The phonological viability check therefore gives it as much credence as a non-word with an underlying nasal, like /soŋ/. In the context of [pimil], /sok/ as [soŋ] would get a score of nearly 0. Thus, the difference between the viable and unviable context is about 1 for the non-variable process, but only about 0.5 for the variable one.

In sum, this model of phonological inference predicts that the effect should be stronger for cases in which a phonological process is non-variable. This is one explanation for the apparently stronger effect of phonological inference on word recognition in the case of Korean obstruent nasalization as opposed to English place assimilation. To determine whether this optional/non-optional distinction, or the perceptual factors discussed in 4.1, do indeed play a determining role in the strength of the effect of phonological inference would require further research that directly compares phonological processes that differ minimally along each of these dimensions.

CONCLUSIONS

As we discussed in the introduction, the role of phonological inference in word recognition is controversial, for several reasons. Perhaps the main reason is that context effects can often be explained as being due to perceptual compensation, which occurs in the mapping of the acoustic signal to a pre-lexical phonetic representation (e.g. Gow 2003, Mitterer et al. 2006ab). This sort of explanation would not account for our data on Korean obstruent nasalization, however. As Darcy et al. (2007) discuss, categorical changes of this type are not well-handled by Gow's (2003) feature parsing model. Further, even if this or some other model of pre-lexical perception could perform categorical neutralization of a contrast, it does not seem likely that the obstruent-nasal contrast is neutralized in this way, given its perceptual robustness, both in general, and in the specific context of a following nasal in Korean (Kabak and Idsardi 2005). And finally, the cross-modal priming task generally appears to tap lexical activation rather than lower-level correspondences. Like others (e.g. Darcy *et al.* 2007), we take the current evidence to show that word recognition involves context effects both at the pre-lexical level, and also at the level of lexical access. Following GM-W, we take the evidence for context effects at the level of lexical access to indicate that listeners perform phonological inference: that they use their knowledge of phonology to determine whether a change is licensed in a particular context. We propose a formalization of this use of phonology in terms of a phonological viability check, whose probabilistic version allows an account of differences between the robustness of phonological inference in the case of non-variable processes (e.g. Korean obstruent nasalization) and variable ones (e.g. English place assimilation). Further research should illuminate the level at which different context effects take place, as well as the influence of factors like perceptual salience and optionality on the strength of these effects.

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APPENDIX

Experimental stimuli and their frequency matched control-stimuli (transcribed as phonological underlying forms and in Yale Romanization)[2]

Place	*Number of syllables*	*Experimental stimuli*	*Unchanged control stimuli*	*Word frequency*		*Experimental stimuli*	*Changed control stimuli*	*Word frequency*	
Coronal	1	/os/ os 'clothes'	/mas/ mas 'taste'	4.9	4.6	/piʧ/ pic 'debt'	kis 'feather'	3.3	2.7
		/k'oʧ^{h}/ kkoch 'flower'	/naʧ/ nac 'daytime'	4.2	4.6	/mit^{h}/ mith 'lower part'	/t'ɨs/ ttus 'meaning'	3.3	4.4
		/piʧ^{h}/ pich 'light'	/jəs/ yes 'taffy'	4.1	3.3				
	2	/kəʧis/ kecis 'lie'	/pəsəs/ peses mushroom'	3.8	3.8	/pak'at^{h}/ pakkath 'outside'	/kɨlɨs/ kulus 'vessel'	4	4.2
		/pulk'oʧ^{h}/ pulkkoch 'fireworks'	/sonʧis/ soncis 'hand gesture'	3.5	3.7	/ius/ ius 'neighbor'	/pəlɨs/ pelus 'habit'	4.1	4.4
		/soŋkos/ songkos 'drill'	/suk^{h}əs/ sukhes 'male (animal) '	2.9	3.3				
Mean				3.9	3.9			3.7	3.9

Continued next page.

[2] Frequency data were collected as follows. A survey was conducted with 20 native Korean speakers. All of them were college students with a mean age of 19 (that is, from a similar population as the subjects in the main experiment). They rated frequency levels of the experimental stimuli from 1 to 5, where 1 is not at all frequent and 5 is very frequent. A paired samples *t*-test did not find a significant difference between the control and experimental stimuli with respect to word frequency, $t(29) = -0.136$, $p > 0.05$.

Labial	1	/tʰop/ thop 'saw'	/nap/ nap 'lead'	2.9	2.8	/kjəp/ kyep 'layer'	/kup/ kup 'heel'	3.1	3
		/kəp/ kep 'cup'	/ip/ ip 'mouth'	4.5	4.5	/ʧʰəp/ chep 'mistress'	/nɨpʰ/ nuph 'swamp'	2.6	2.4
	2	/kuklip/ kuklip 'national'	/susɨp/ susup 'apprentice'	3.7	3.1	/ʧakəp/ cakep 'work'	/pæk'op/ paekkop 'navel'	4	3.5
		/mulɨp/ mulup 'knee'	/suip/ suip 'import'	4	4.3	/kinkɨp/ kinkup 'emergency'	/ʧoŋhap/ conghap 'synthesis'	4.1	4.2
		/siləp/ silep 'unemploy-ment'	/wəlkɨp/ welkup 'salary'	3.5	4.2	/moʧip/ mocip 'recruitment'	/mjənʧəp/ myencep 'interview'	4.2	4.3
Mean				3.7	3.8			3.6	3.5
Velar	1	/mok/ mok 'neck'	/hɨlk/ hulk 'soil'	4.1	4.1	/sok/ sok 'inner part'	/ak/ ak 'vice'	3.9	3.3
		/t'ək/ ttek 'rice cake'	/kuk/ kuk 'soup'	4.2	4.2	/s'uk/ ssuk 'mugwort'	/pʰok/ phok 'width'	3.1	3.1
		/tʰək/ thek 'jaw'	/ʧʰæk/ chaek 'book'	4.3	4.7				
	2	/totuk/ totuk 'thief'	/kolmok/ kolmok 'side street'	3.9	3.7	/mokjok/ mokyok 'bath'	/kənʧʰuk/ kenchuk 'architecture'	4.4	4.7
		/kaʧok/ kacok 'family'	/sæpjək/ saepyek 'dawn'	4.5	4.4	/ʧənjək/ cenyek 'evening'	/səntʰæk/ senthaek 'selection'	4.6	4.5
						/puəkʰ/ puekh 'kitchen'	/sɛtʰak/ seythak 'laundry'	4	4
Mean				4.2	4.2			4	3.9

Total mean		3.9	4	3.8	3.8