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Error patterns of native and non-native listeners' perception of speech in noise

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Abstract: Speech perception in noise requires both bottom-up sampling of the stimulus and top-down reconstruction of the masked signal from a language model. Previous studies have provided mixed evidence about the exact role that linguistic knowledge plays in native and non-native listeners' perception of masked speech. This paper describes an analysis of whole utterance, content word, and morphosyntactic error patterns to test the prediction that non-native listeners are uniquely affected by energetic and informational masks because of limited information at multiple linguistic levels. The results reveal a consistent disadvantage for non-native listeners at all three levels in challenging listening environments.

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1. Introduction

The cognitive demands of speech perception are amplified in natural listening conditions where persistent speech and non-speech noise causes informational and energetic masking of the speech signal (Mattys *et al.*, 2012). The demands of speech perception in noisy conditions (hereafter, SPIN) are even greater for non-native listeners, who have less experience with the language they are hearing and interference from knowledge of their first language (Meador *et al.*, 2000). Non-native listeners reliably perform worse than native listeners in perceiving most types of masked speech (see Garcia Lecumberri *et al.*, 2010, for review). Both informational masks and energetic masks adversely affect non-native listeners' comprehension more than native listeners overall (Cooke *et al.*, 2008), but the exact mechanisms underlying this disadvantage are not entirely clear. In this study, we expand upon an analytic approach described by Smith and Fogerty (2017) to classify different types of errors committed by native and non-native listeners under different masking conditions.

Evidence from both native and non-native listeners highlights the importance of synthesizing top-down linguistic knowledge with bottom-up acoustic information for SPIN (Rönnberg *et al.*, 2013). Glimpsing is one proposed mechanism by which listeners integrate a degraded bottom-up signal with a top-down language model. When listeners perceive fragments of interrupted speech, they actively reconstruct the surrounding context based on their linguistically-informed predictions (Cooke, 2006). Listeners with less language knowledge will have less such top-down information to apply to the inference, and thus, an important contribution to the non-native listener disadvantage in SPIN is likely incomplete knowledge of the target language (Garcia Lecumberri *et al.*, 2010). This view is supported by the elimination of native vs non-native differences in energetic masking when linguistic cues to the stimulus (e.g., syntactic, semantic, or phonotactic context) are not available in the signal (Garcia Lecumberri *et al.*, 2010).

Nevertheless, non-native listeners also appear to apply top-down knowledge in speech perception to overcome an energetic mask, though to less advantageous ends than native-listeners (Bradlow and Alexander, 2007). Conflicting cues from a listener's

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native language and the (non-native) target language may thus be a source of disadvantage for the non-native listener (Golestani *et al.,* 2009). Cooke and colleagues (2008) reported that while the overall native listener advantage is preserved for both steady-state noise and multi-talker masks, non-native learners were more adversely affected by a talker mask than could be accounted for by its energetic contribution alone, indicating a greater sensitivity to interfering information from the talker mask for non-native listeners relative to native listeners.

Smith and Fogerty (2017) provided further evidence for interaction in native speakers with a microscopic analysis of error patterns in SPIN to discriminate between phonemic part-word errors and whole-word errors in sentence perception as a function of glimpse size. This study identified two important patterns in SPIN errors: (1) Listeners tended to reconstruct words from perceived fragments. (2) Native listeners were nearly twice as likely to substitute whole, syntactically- and semantically-plausible words instead of substituting phonologically similar words that would match the fragments of input. This finding highlights the importance of higher level lexical or syntactic predictions in SPIN, even as the expense of lower-level phonemic similarity.

In the present study, we compare listeners' error patterns at a level of linguistic knowledge not previously examined in SPIN experiments. This study examines the error rates in whole utterances, in content words, and in morphosyntactic affixes and closed-class words for native and late-L2-onset, non-native listeners. Many morphosyntactic errors result in partial changes of the target word (e.g., substituting *cat* for *cats*) and to closed-class words (e.g., omissions of definite article *the*), but these errors may be mitigated by making morphosyntactic inferences from the context. While the lexical knowledge that appears to underlie the results in Smith and Fogerty's (2017) paradigm may be quickly attained by second language learners, masked morphosyntactic information could only be inferred by using broader sentential context, providing a stronger contrast of native vs non-native listeners. We ask how native and non-native listeners' error patterns differ across these levels and across four types of mask:

(1) We predicted that non-native listeners to English speech would be *more* susceptible to morphosyntactic errors than native listeners, as a result of their incomplete language knowledge. Mandarin Chinese has very different morphosyntactic rules from English, particularly in pluralization, tense markers, subject-verb agreement, and use of articles. (2) We predicted that informational masks [1-Talker (1T) and 2-Talker (2T)] would increase the magnitude of non-native disadvantage relative to the energetic masks [speech-shaped noise (SSN) and 8-Talker (8T); see Cooke *et al.*, 2008]. (3) Because these three types of errors draw on linguistic features with different base rates (number of content words, number of morphemic affixes, etc.), we made no prediction about the main effect of error type, but we asked whether the interaction between mask type and error type could differ between native and non-native listeners (i.e., a three-way interaction) indicating that word and morphosyntactic errors were differently sensitive to mask types.

2. Method

2.1 Participants

We acquired archived behavioral SPIN data from the pre-testing regimen in a recent electrophysiological study (Reetzke *et al.*, 2017) for this study. The dataset included 15 native and 15 non-native speakers of American English, recruited at the University of Texas at Austin. One non-native speaker was excluded from the present analysis because they did not complete the behavioral tasks. The native group was composed of speakers of American English who reported no significant experience with another language. Non-native participants were Mandarin-English bilinguals, born and raised in mainland China, spoke Mandarin Chinese as their native language, did not begin learning English formally until after the age of 6 [range = 7–16 yr, mean = 10.1 yr, standard deviation (s.d.) = 2.6 yr], and lived in the United States no more than 6 yr (range = 1 to 6 yr, mean = 2.0 yr, s.d. = 1.6 yr).

The native and non-native groups were comparable on age, sex, and non-verbal intelligence. (See Table 1.) Participants reported no previous history or diagnosis of speech, language, or neurodevelopmental disorders. All participants had normal hearing defined as air and bone conduction thresholds < 20 dB hearing level at octave frequencies from 250 to 8000 Hz, as measured by an Equinox 2.0 PC-Based Audiometer (Interacoustics, Middelfart, Denmark). Participants had no significant music experience (<6 yr), according to a music and language questionnaire (Li *et al.*, 2014). The groups did not significantly differ on this measure [$t(27) = 1.19$, $p = 0.24$].

Participants completed the Test of Adolescent and Adult Language (TOAL-4; Hammill *et al.*, 2007) as a standard measure of English language proficiency. The mean TOAL-4 composite for spoken English proficiency differed greatly between the native and non-native groups. Native speakers scored 107 (s.d. = 12), and non-native speakers scored 65 (s.d. = 10), $t(27) = 11.0$, $p < 0.001$.

2.2 Stimuli

The masked sentence stimuli were developed for previous speech in noise studies (for details, see Chandrasekaran *et al.*, 2015; Van Engen, 2012; Xie *et al.*, 2015). Sixty-four target sentences from the Revised Bamford-Kowal-Bench Standard Sentence Test (Bamford and Wilson, 1979) were recorded by a female native speaker of American English (Van Engen, 2012). Target sentence stimuli were organized into four masking conditions: sixteen 1T informational mask trials, sixteen 2T informational mask trials, 24 steady-state SSN energetic mask trials, and eight 8T trials. Previous research has demonstrated that the 8T mask produces primarily energetic masking, at the same level as SSN (Brungart *et al.*, 2009).

The SSN condition was composed from a steady-state white noise which was then shaped to a speech-like spectrum based on long-term average spectra acquired from 240 spoken sentences in the original corpus (Van Engen *et al.*, 2010). Recordings of eight additional female, native speakers of American English reading a different set of sentences were used to generate the 1T, 2T, and 8T masks (Van Engen *et al.*, 2010; see Chandrasekaran *et al.*, 2015 and Xie *et al.*, 2015 for details). In all trials, the mask was 5 dB greater than the target sentences [signal-to-noise ratio (SNR) = –5 dB), consistent with the previous published use of these stimuli, wherein the SSN and 1T conditions elicited above-chance and below-ceiling performance (Chandrasekaran *et al.*, 2015).

2.3 Procedure

Participants were seated in a SoundEgg sound-attenuated seat with a personal computer and Sennheiser HD280 headphones. They were instructed that they would be listening to several recorded sentences in different types of noise, and the target sentence would begin about half a second after the noise. Participants were asked to type the target sentence or their best guess into the computer for each trial. The computer volume was adjusted to a comfortable level, and participants listened to the 64 stimulus trials in a uniquely randomized order for each participant. Responses were scored according to the error analysis described below.

2.4 Error analysis

In contrast with keyword counts often used for speech in noise tasks (e.g., Chandrasekaran *et al.*, 2015; Van Engen *et al.*, 2012; Xie *et al.*, 2015), this analysis examined whole utterance, content word, and morphosyntactic level errors. Participants' typed responses and their respective target sentences were aligned by a custom implementation of the Needleman–Wunsch algorithm, a dynamic global alignment algorithm primarily used in bioinformatics (Needleman and Wunsch, 1970). In the original algorithm, three scores govern the optimal alignment: a match award, a mismatch penalty, and a gap penalty. The optimal alignment between two sequences is chosen by maximizing matches between the sequences' elements and minimizing mismatches and gaps. This search process is illustrated in Fig. 1.

Our implementation compares each word between two sentences (target and response) and adds one additional parameter to award pairs of words with Levenshtein distances ≤ 2. This adjustment encourages alignment for words with similar spellings such as some homonyms and rhymes when an exact match is not found. The alignment step produces two optimally-aligned sentences with equal numbers of words, allowing for gaps, which are represented by the token "_" (see Fig. 1). Errors are then calculated by examining each word pairing in the alignment.

After alignment all words were lemmatized and tagged for part of speech by the Pattern module (De Smedt and Daelemans, 2012), a Python toolkit which quickly

Table 1. Participant demographics, group means and s.d.

Group	N	Age	Sex	KBIT Score	Music Experience	TOAL-4
Native	15	22.5 (3.7)	9 F/6 M	118 (8.4)	1.8 yr (2.4)	107 (12)
Non-native	14	25.1 (3.4)	8 F/6 M	124 (7.4)	0.9 yr (1.8)	65 (10)

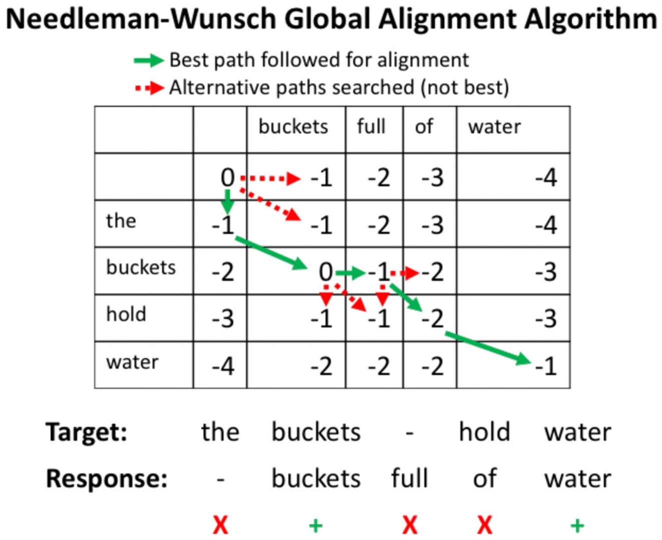

Fig. 1. (Color online) Procedure for aligning target and response sentences. Each word pair matched by the aligner is compared for word-level or morphosyntactic errors.

and accurately performs part-of-speech tagging, lemmatization, spelling suggestions, and other natural language processing tasks in Python 2.7.10. If a pair of aligned words matched in their root forms but not in the original target and response, a morphosyntactic error was recorded. Additionally, if both words were function words or if a function word was aligned with a gap token, a morphosyntactic error was recorded. If both words were content words or if a content word was aligned with a gap token, a content word error was recorded. If one word in a pairing was a function word and the other a content word, one morphosyntactic error and one content word error were each recorded.

Finally, if none of the roots for content words from the key sentence appeared in the response, the entire trial was reclassified as "Did Not Hear" (DNH). This distinction is important because sometimes participants failed to transcribe any response at all or fully transcribed a masker sentence instead of the target. These whole utterance level errors are counted separately, as they do not reflect specific word-level or morphosyntactic changes in the perceived signal.

The code for performing this error analysis and the de-identified dataset are both publicly available (Riggs *et al.*, 2018).

3. Results and discussion

3.1 DNH Trials

The DNH data were coded as 1 for a trial with a DNH error and 0 for all other trials, and they were fit to a logistic mixed-effects model (using the lme4 package for R; Bates *et al.*, 2014) with a random effect of subject and fixed effects for non-native relative to native (reference level) listener groups and for each of the talker masks (1T, 2T, 8T) relative to SSN (reference level). We also estimated the interaction between group and each talker mask. The left panel of Fig. 2 depicts the mean subject-level proportion of DNH trials in each group for each type of mask.

Effects of listener group and each of the talker masks in the model were statistically significant ($p < 0.001$), as well as two of the three interaction terms: A negative interaction term between non-native and 1T ($z = -2.95$, $p = 0.003$) indicated a smaller non-native disadvantage relative to the SSN condition. Likewise, in the 2T condition, a negative interaction with non-native ($z = -4.98$, $p < 0.001$) also indicated a smaller non-native disadvantage in 2T as compared to SSN. A much smaller interaction (half magnitude relative to 2T) was observed for 8T ($z = -2.05$, $p = 0.04$), providing weak evidence of a change in the non-native disadvantage between 8T and SSN conditions in the frequency of DNH responses.

Therefore, we find support for a non-native disadvantage at this whole-utterance level. Non-native listeners were significantly more likely to fail to transcribe any sentence at all under the purely energetic masking condition (SSN). This effect was attenuated for informational masks, 1T and 2T, suggesting that the non-native listeners benefited from the extra glimpses of target speech more than they were adversely affected by distractors in the informational mask.

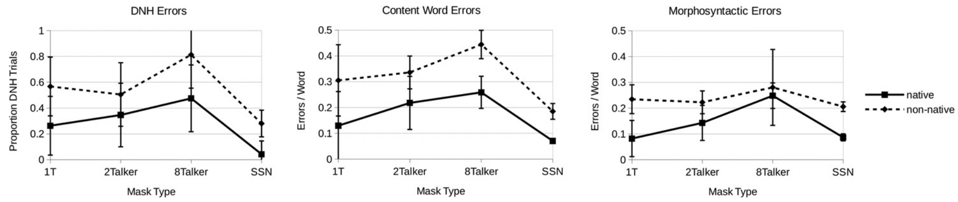

Fig. 2. Mean error rates in native and non-native listeners. Left panel, the proportion of DNH responses per condition for both listener groups. Middle panel, content word-level error rates in native (solid line) and non-native (dashed line) listeners. Right panel, morphosyntactic errors for native (solid line) and non-native (dashed line) listeners. Error bars denote two standard errors of the mean.

Beyond the weak interaction with non-native status, the fixed effect of 8T was significant ($z = 10.02$, $p < 0.001$), indicating a higher probability of producing DNH responses than SSN across the two groups. The fixed effects of non-native (vs native) group, 1T (vs SSN), and 2T (vs SSN) were all larger than their respective interaction terms. Thus, while the non-native disadvantage was attenuated for 1T and 2T masks, the non-native listeners were still more likely to produce DNH trials overall, and all three talker masks resulted in more DNH trials across native and non-native listeners than SSN.

In contrast with the 1T and 2T findings, the weaker interaction for non-native disadvantage between the 8T and SSN suggests that 8T mask coverage was more similar to steady-state noise (consistent with Brungart *et al.*, 2009). However across groups, the 8T mask yielded significantly more errors than SSN at the same SNR, which indicates that some additional masking occurred in the 8T condition besides the purely energetic contribution, contrary to the findings of Freyman *et al.* (2007).

3.2 Content word and morphosyntactic errors

After excluding all DNH trials from the dataset, we fit a linear mixed-effects model (using the lmerTest package for R; Kuznetsova *et al.*, 2017) to the content word and morphosyntactic error rates per word in each trial, with a random effect of subject and fixed effects for non-native relative to native listener, morphosyntactic error relative to content word error, and each of the talker masks (1T, 2T, 8T) relative to SSN. We summarized the fixed effects in this model with a three-way analysis of variance (ANOVA): 2 (group) by 2 (error type) by 4 (mask type).

The ANOVA found a marginally significant three-way interaction between group, mask, and error type [$F(3,2383) = 2.39$, $p = 0.07$]. The two-way interactions between group and error type and between mask type and error type were both significant [group × error $F(1,2383) = 4.79$, $p = 0.03$; mask × error $F(1,2383) = 10.82$, $p < 0.001$]. The two-way interaction between group and mask was not significant ($p = 0.91$), although its variance may have been explained by the three-way interaction term. All main effects were statistically significant ($p < 0.001$) but interpretable only in relation to their significant interaction terms, addressed in the follow-up analyses.

In the combined content words and morphosyntax errors, we found further confirmation of a non-native disadvantage in SPIN. However, our prediction that morphosyntax would be especially sensitive to non-native status due to additional linguistic information required to resolve morphosyntactic ambiguity (Meador *et al.*, 2000) is only equivocally supported. A significant ($p = 0.03$) two-way interaction between group (native vs non-native) and error type, coupled with a marginally significant three-way interaction (group × error type × mask type) suggests that the non-native disadvantage might differ between the content word and morphosyntactic error measures. Bonferroni-corrected *post hoc t* tests on the subject-level mean error rates (estimated first for each mask type, and then averaged across conditions to balance against the uneven number of trials per mask type) for native vs non-native listeners revealed a significant non-native disadvantage in both content word errors [Welch's two-sample $t(27) = 3.46$, $p_{\mathrm{Bonf}} = 0.004$, Cohen's $d = 1.28$] and morphosyntactic errors [Welch's two-sample $t(25) = 2.88$, $p_{\mathrm{Bonf}} = 0.016$, Cohen's $d = 1.08$]. However, while it appears that both error measures yield highly significant non-native disadvantages, the effect size in this dataset slightly favors content words over morphosyntax (although the two effect sizes did not statistically differ).

We re-estimated the linear mixed effects models separately for content word errors and for morphosyntactic errors, applying a 2 (group) by 3 (mask type) ANOVA for each model. For content word errors, the main effects of group [$F(1,35) = 14.21$, $p < 0.001$] and mask type [$F(3,1190) = 35.07$, $p < 0.001$] were statistically significant. No significant interaction was observed ($p = 0.59$), see middle panel of Fig. 2. The same was true for the morphosyntactic errors. Main effects of group [$F(1,38) = 16.76$, $p < 0.001$] and mask type [$F(3,1193) = 9.28$, $p < 0.001$] were statistically significant, while the interaction was not ($p = 0.11$), see right panel of Fig. 2. The main effects of groups supported the non-native disadvantage in each error type.

We performed planned comparisons between SSN and the three talker mask types using Bonferroni corrected paired *t* tests on subject-level averages. In the content word errors, 2T and 8T masks significantly exceeded SSN (both $p_{\mathrm{Bonf}} < 0.001$), but in the morphosyntactic errors, only the 8T significantly differed from SSN ($p_{\mathrm{Bonf}} = 0.008$). This finding aligns with the DNH results, wherein 8T produced significantly more errors than SSN. In both error conditions, listeners' 8T performance seems more closely linked to linguistic interference (i.e., number of talkers) than to mask energy (i.e., mask coverage, when signal-to-noise is held constant). However, the absence of significant group $\times$ mask type interactions in the two-way ANOVAs of either error type do not provide any support for the observation of Cooke *et al.* (2008) of increased non-native disadvantage under informational masking.

3.3 Balanced mask types

In a final follow-up analysis, we addressed the possible role of the unequal number of trials for different mask types. Previous research (see Brouwer and Bradlow, 2014; Freyman *et al.*, 2007; Watson, 1987) demonstrated significant effects of uncertainty in performance on tone or speech perception, which may have affected the relative difficulty of each mask condition based on its frequency in a given task. To address this issue, we selected the first eight trials of each mask type for every subject, so that every mask type had the same degree of exposure and opportunities for participants to learn the noise properties. We then repeated all of the analyses described in Secs. 3.1 and 3.2.

The results were nearly identical, with the following two exceptions: In the $2 \times 2 \times 4$ (group $\times$ error type $\times$ mask type) ANOVA, the interaction of group $\times$ error type was no longer statistically significant [original: $F(1,2383) = 4.79$, $p = 0.03$; subset: $F(1,1013) = 1.51$, $p = 0.22$]. The planned comparison of 1T and SSN content word errors significantly differed [original: $t(26) = 1.94$, $p_{\mathrm{Bonf}} = 0.188$; subset: $t(25) = 2.61$, $p_{\mathrm{Bonf}} = 0.046$]. Thus, our follow-up analysis on the balanced subset of data did not change the interpretation of our main findings.

4. Summary and conclusions

In this study, we examined three types of errors made by native and non-native listeners to spoken English sentences under energetic and informational masking. Based on previous research, we expected non-native listeners to perform differently from native listeners across these conditions as a result of their incomplete language knowledge (Garcia Lecumberri *et al.*, 2010). This prediction was supported by lower non-native listener performance in all three error types, and the present study identifies significant differences at all three levels separately. The evidence in this study tentatively suggested that content word errors increased more for non-native (relative to native) listeners than morphosyntactic errors, but effects at both levels were large and did not greatly differ in magnitude. In contrast to some previous studies of sentence (Cooke *et al.*, 2008) and consonant (Garcia Lecumberri and Cooke, 2006) perception, we did not find evidence that the informational masks were disproportionately more difficult for non-native listeners relative to the non-native disadvantage in a steady-state noise energetic mask, although the 8T mask produced more errors on all three measures than a steady-state SSN mask, suggesting that it provided both energetic and informational masking (contrary to Brungart *et al.*, 2009 and Freyman *et al.*, 2007).

The present findings should be considered in the context of a few important limitations. The non-native listeners in this study were native speakers of one language (Mandarin Chinese), selected for its particular differences from English in morphosyntax. However, these non-native listeners were relatively diverse in their experience with English, likely adding variance to their error rates that was not accounted for in this brief investigation. Further applications of our proposed error analyses to new participant groups and mask types would help to clarify these issues as well as potentially offering important new insights on non-native speech in noise perception. To that end, we have made the analysis code and sample data publicly available (Riggs *et al.*, 2018) to enable other researchers to implement this approach with their own data.

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