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Lexical frequency effects in English and Spanish word misperceptions

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1 **Abstract:** When listeners misperceive words in noise, do they report
2 words that are more common? Lexical frequency differences between
3 misperceived and target words in English and Spanish were examined
4 for five masker types. Misperceptions had a higher lexical frequency
5 in the presence of pure energetic maskers, but frequency effects were
6 reduced or absent for informational maskers. The tendency to report
7 more common words increased with the degree of energetic masking,
8 suggesting that uncertainty about segment identity provides a role for
9 lexical frequency. However, acoustic-phonetic information from an in-
10 formational masker may additionally constrain lexical choice.

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11 1. Introduction

12 It is a common experience for listeners to misperceive words under challenging conditions,
13 but the manner in which degraded sensory evidence and prior language experience interact
14 to produce the resulting ‘slips of the ear’ is poorly understood. One form of prior information
15 that listeners might be forced to use in noise is lexical frequency. It has long been known
16 that common words are more likely to be correctly recognised in noise than less frequent
17 words^{1,2} but there are conflicting findings as to whether *misperceptions* are themselves more
18 common words than corresponding intended ‘target’ words in noise.

19 Several studies have examined lexical frequency effects in naturalistic compilations of
20 reported real-life misperceptions^{3–5}. Using a meta-corpus composed of previous compilations
21 of misperceptions, Tang⁶ found an inconsistent pattern of lexical frequency effects across
22 corpora, but overall, misperceptions were not more common words than target words. One
23 issue with naturalistic corpora is the paucity or absence of metadata describing the context
24 in which each misperception occurred. For example, neither audio evidence for each speech
25 token nor information about the presence, nature and level of any maskers is available for
26 further analysis.

27 Very few studies have measured lexical frequency effects in controlled masking condi-
28 tions. Pollack et al.⁷ analysed incorrect responses from an earlier study⁸ in which listeners
29 identified 144 distinct monosyllabic English words belonging to one of eight frequency classes,
30 presented in white noise at signal-to-noise ratios (SNRs) in the range -5 to $+25$ dB. Pollack
31 et al. found the median lexical frequency of incorrect responses to be independent of the

32 word frequency class of the stimulus. However, listeners reported higher frequency misper-
33 ceptions at lower SNRs. Listeners in a study by Felty et al.⁹ identified subsets of a 1428
34 English word sample presented in 6-talker babble at SNRs of 0, +5 and +10 dB. A clear
35 lexical frequency difference effect was observed: misperceptions were more common words
36 than target words. A similar study¹⁰ using Spanish words presented in five maskers at SNRs
37 in the range -13 to $+1$ dB found that, across maskers, the lexical frequency of misperceived
38 words was significantly higher than target words. However, no breakdown by masker type
39 was presented.

40 Taken together, previous studies present an inconsistent picture of whether mispercep-
41 tions reported by listeners under conditions of actual or potential masking (the latter cor-
42 responding to the case of naturalistic corpora) tend to be more common than target words.
43 This is not altogether unexpected, since the varied masking conditions employed in the these
44 studies might have modulated the role of lexical frequency in different ways. One key dis-
45 tinction is between energetic and informational masking. While pure energetic maskers such
46 as stationary or modulated noise act to distort or partially remove acoustic evidence for the
47 target word, speech-based informational maskers can in principle contribute fragments of
48 their own acoustic-phonetic information to the melange which forms the basis for a listener's
49 lexical decision, enabling misperceptions to result from misallocation of masker fragments
50 to the final word interpretation. The current study of lexical frequency effects in noise was
51 motivated by the absence of prior studies involving comparisons of (i) more than one masker;
52 and (ii) maskers with both an energetic and informational component.

53 2. Datasets

54 Lexical frequency effects were investigated for consistent word misperceptions in noise in
55 two recent, extensive, open-source datasets of Spanish (SP)¹¹ and English (EN) words¹².
56 Consistent misperceptions are defined in these datasets as tokens for which no fewer than
57 six listeners reported the same misperception in response to a given target word presented in
58 noise. Both datasets were elicited in a similar manner, but while the EN dataset used three
59 maskers (speech-shaped noise, SSN; 3-talker babble-modulated noise, BMN3; 4-talker bab-
60 ble, BAB4), the SP dataset additionally employed 1-talker babble-modulated noise (BMN1)
61 and 8-talker babble (BAB8). Babble maskers were generated by random concatenation of
62 target words to reach the required babble density^{11,12}. Misperceptions were elicited at a
63 range of SNRs (Table 1), values chosen in pilot tests to maximise the chance of consistent
64 confusions, motivated by the finding that too-high SNRs lead to few errors, while too-low
65 SNRs tend to produce inconsistent errors.

66 The online Spanish and English corpora contain 3235 and 3207 misperceptions respec-
67 tively. For the current study these counts were reduced to 3126 and 3198 after excluding
68 tokens based on the following criteria: (i) 82 Spanish confusions were found to result from
69 SNRs outside the desired SNR range¹¹; (ii) for 11 examples (8 Spanish) no lexical frequency
70 data was available for the confused word; and (iii) for 25 examples (19 Spanish) the reported
71 misperception was not present in the relevant pronunciation dictionary. Table 1 provides
72 a breakdown of the number of misperceptions for each language/masker pairing along with
73 details of the SNRs that led to the misperceptions.

Table 1. *Misperception counts for the Spanish (SP) and English (EN) datasets in each masking condition, alongside statistics of the SNRs used during their elicitation, which varied within the range shown. ‘Unique’ refers to counts after removing duplicates (see section 3.1).*

Masker	Dataset	Counts		SNRs (dB)			
		Total	Unique	mean	std.	min	max
SSN	SP	609	437	-5.4	0.9	-7.0	-4.0
	EN	1068	759	-5.5	0.9	-7.0	-4.0
BMN3	SP	732	533	-5.3	1.4	-7.9	-3.0
	EN	1196	903	-5.5	1.4	-8.0	-3.0
BMN1	SP	777	611	-9.9	1.8	-13.0	-7.0
BAB8	SP	419	345	-1.2	1.3	-4.0	1.0
BAB4	SP	589	501	-0.9	1.2	-3.0	1.0
	EN	934	818	-1.2	1.2	-3.0	1.0

74 One difference between the two published corpora lies in the source of lexical frequency
75 estimates for target and misperceived words. Estimates for the SP dataset are derived from
76 the CREA Spanish word frequency list¹³, expressed in occurrences per million words, while
77 equivalent data for the EN dataset come from the SUBTLEX-UK corpus¹⁴, expressed in

78 Zipfs. The Zipf scale is defined as \log_{10} (frequency per billion words) and ranges from
79 around 1 (very low frequency words) to 7 (extremely common words, mainly function words
80 and pronouns). For example, in the current datasets, common words “por” and “we” have
81 a Zipf value around 7 and the far less common words “bromeas” and “fifteenth” have values
82 near to 2. The Zipf scale is argued to avoid the problem of interpreting negative values that
83 arise from log-transformed counts per million words that occur when counts are derived from
84 very large corpora¹⁴. To ease comparability in the current study, lexical frequencies in the
85 SP dataset were derived by converting values to Zipfs. Mean word frequencies for the SP
86 and EN datasets are very similar, at 4.23 (std. 0.70) and 4.20 (std. 0.81) Zipfs respectively.

87 **3. Results**

88 *3.1 Lexical frequency differences*

89 Lexical frequency differences were computed by subtracting the frequency of the target word
90 from that of the misperception, so that positive lexical frequency differences correspond to
91 misperceptions that are more common words.

92 Across masking conditions, mean lexical frequency differences for SP and EN are 0.39
93 and 0.44 Zipfs respectively, indicating that, on average, misperceptions are 2.5-2.75 times
94 more common than target words. A breakdown by type of masker (Fig. 1) reveals that the
95 lexical frequency difference originates largely in the pure energetic maskers (SSN, BMN1,
96 BMN3); the two maskers with an informational component (BAB4, BAB8) show a much
97 smaller lexical frequency effect. For example, on average, Spanish misperceptions reported

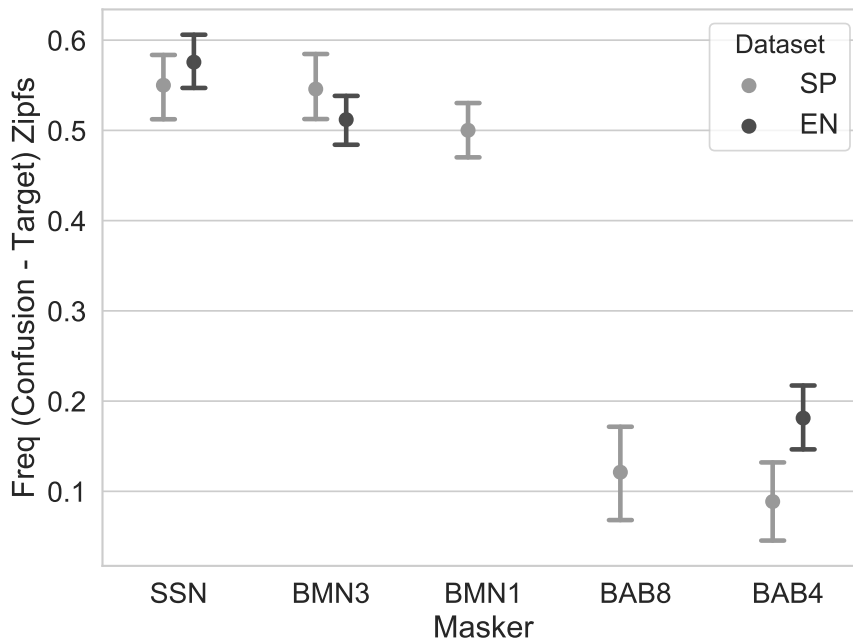


Fig. 1. Mean lexical frequency differences for each masker and dataset. Error bars indicate ± 1 standard error. The Zipf scale is defined as \log_{10} frequency per billion words (see text for details).

98 in SSN are over 3.5 times more common than their corresponding targets, while Spanish
 99 misperceptions reported in BAB4 occur only 1.2 times as frequently.

100 Lexical frequency differences for the three maskers in common in the SP and EN datasets
 101 are very similar. A two-factor analysis of variance based on the common maskers confirms
 102 a differential effect of masker type [$F(2, 5122) = 86.3, p < .001, \eta^2 = 0.033$], a lack of effect
 103 of dataset [$p = .33$] and the absence of an interaction between the two [$p = .20$].

104 To test for any potential influence from the different sources of word frequency statistics
 105 used to compile the EN and SP datasets, lexical frequency counts for the SP dataset were

106 replaced by those from the SUBTLEX-ESP corpus¹⁵, which used a similar subtitle-based set
 107 of materials as those underlying the EN corpus¹⁴. A near-identical pattern [$F(2, 5122) =$
 108 $89.3, p < .001, \eta^2 = 0.033$] was observed.

109 To eliminate further possible confounds, we examined four factors that might have
 110 influenced the pattern of lexical frequency differences across masker types.

111 *3.1.1 Words from the masker*

112 Misperceptions in the EN and SP datasets occasionally correspond to complete words con-
 113 tained in the BAB4 masker. Since maskers were constructed from the same set of speech
 114 materials as the target words, a mean lexical frequency difference of zero is to be expected
 115 for these cases, leading to a potential source of bias. Such cases amount to some 316 tokens
 116 (around 5% of the combined datasets), of which 269 occur in the EN dataset. After exclud-
 117 ing these cases, the lexical frequency difference for the BAB4 masker in EN increases from
 118 0.18 to 0.31 Zipfs, while for SP the increase is more modest, from 0.09 to 0.12 Zipfs. How-
 119 ever, a significant masker effect remains [$F(2, 4806) = 47.1, p < .001, \eta^2 = 0.019$], indicating
 120 that the occasional reporting of complete words from the babble might account for part of
 121 the limited lexical frequency effect in the EN dataset, but has almost no impact on the SP
 122 corpus.

123 *3.1.2 Word length differences*

124 Shorter words tend to be more common, and different maskers may result in different patterns
 125 of phoneme deletion. For example, the quasi-stationary SSN masker might be expected to
 126 leave more energetic target components near to syllable nuclei intact, while maskers with

127 significant temporal modulation might produce a more uniform pattern of deletions across
 128 phonemes.

129 For the misperceptions of the current datasets, length in phonemes is indeed inversely-
 130 related to lexical frequency [EN: $r = -0.38$, SP: $r = -0.30$, both $p < .001$]. However,
 131 a significant masker effect remains, albeit with a reduced effect size, after excluding tar-
 132 get/misperception pairs of differing phoneme length [$F(2, 1999) = 21.2, p < .001, \eta^2 = 0.021$].
 133 Combining the equal-length criterion with exclusion of words from the masker (Section 3.1.1)
 134 leads to a further reduction in effect size [$F(2, 1929) = 13.9, p < .001, \eta^2 = 0.014$]. In-
 135 terpretation of causality in the relationship between lexical frequency and word length is
 136 problematic⁹, since misperceptions may be shorter *because* they are of higher frequency.

137 3.1.3 Influence of extreme Zipf values

138 To check whether lexical frequency differences were influenced by extreme Zipf values, we
 139 examined the ratio of the number of target-misperception pairs with a positive lexical fre-
 140 quency difference to those with a negative lexical frequency difference, a metric that removes
 141 the influence of absolute frequency values. Across maskers, the ratio produces a clear bi-
 142 modal pattern similar to that seen in Fig. 1. For example, about 2.8 times as many pairs
 143 have a positive difference for the SSN masker, a ratio that decreases to 1.3 for the BAB4
 144 masker.

145 3.1.4 Duplicate target-misperception pairs

146 Due to the procedure used to generate new speech-in-noise tokens on demand during elici-
 147 tation of the EN and SP datasets, which involved random selection of a target word from a

148 base corpus, both datasets contain a number of duplicate target-misperception pairs (note
 149 that even though targets were presented multiple times, they may have come from different
 150 talkers and were mixed at varying SNRs with potentially different maskers). For instance,
 151 the target word ‘perverse’ (3.13 Zipfs) was misperceived as the more common word ‘reverse’
 152 (4.15 Zipfs) on two occasions. A re-analysis limited to unique pairs only (counts of which
 153 are indicated in Table 1) produces a highly-similar pattern to that seen in Fig. 1 and a clear
 154 effect of masker type [$F(2, 3945) = 70.0, p < .001, \eta^2 = 0.034$], ruling out any influence from
 155 duplicate pairs.

156 3.2 Energetic masking

157 Although the lexical frequency differences observed in Fig. 1 vary across maskers, these
 158 differences might not stem from masker type *per se* but rather from differences in degree of
 159 energetic masking, which were not fixed or equalised across maskers (recall that SNR ranges
 160 were chosen to favour the elicitation of misperceptions for that masker type). As noted in the
 161 Introduction, one study⁷ found that listeners were more likely to report words with a higher
 162 lexical frequency in noise at low SNRs. Our results also show a negative correlation between
 163 the size of the lexical frequency difference and SNR across maskers [SP: $r = -0.15$, EN:
 164 $r = -0.12$; both $p < .001$]. However, SNR is known to be a poor predictor of intelligibility
 165 when comparing maskers which vary in their spectro-temporal modulation properties¹⁶. As
 166 an alternative proxy for pure energetic masking, glimpse percentages were computed for the
 167 two datasets (Fig. 2). Glimpse percentages have been shown to provide reasonable first-order
 168 predictions of intelligibility for a range of different speech and masker types¹⁷.

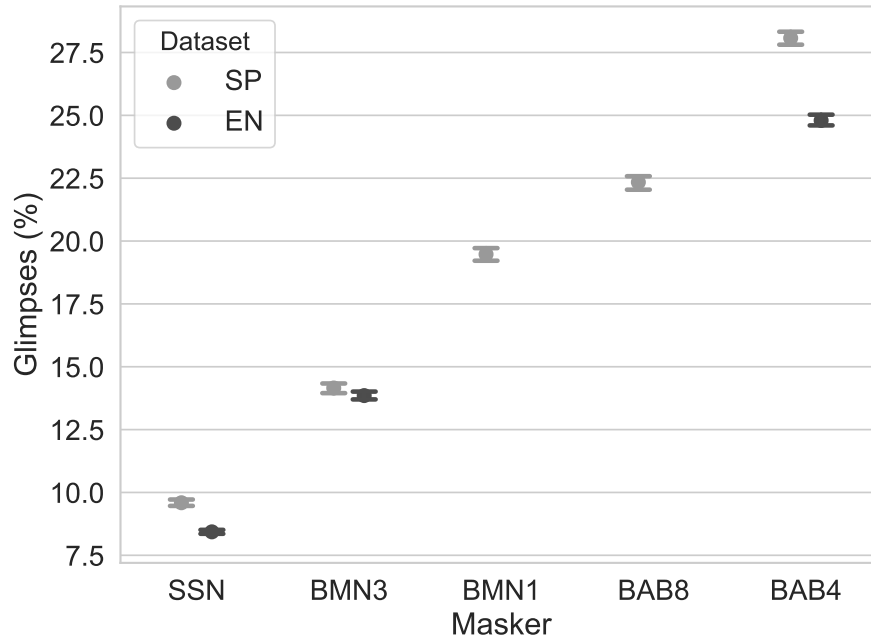


Fig. 2. Mean glimpse percentages for each dataset and masker combination. Glimpse percentage is defined here as the percentage of spectro-temporal regions in an auditory ‘spectrogram’ where the target word energy exceeds that of the masker. Auditory spectrograms were computed by processing the target word and masker independently through a 55-channel gammatone filterbank with centre frequencies in the range 80-8000 Hz, followed by extraction of the Hilbert envelope, smoothing with a 0.8 ms time constant, and downsampling to 100 Hz. Error bars indicate ± 1 standard error.

169 Mean glimpse percentage differs across maskers [$F(2, 5122) = 4711, p < .001, \eta^2 = 0.64$]
 170 for the ranges of SNRs used here. Moreover, glimpse percentage is lower for the three
 171 pure energetic maskers than for the two babble maskers, suggesting that part of the lexical

172 frequency effect seen in Fig. 1 could be due to scarcity of information about the target that
173 is predicted to survive masking. Nevertheless, energetic masking cannot entirely explain
174 the across-masker disparity between lexical frequency differences. For example, BMN1 and
175 BAB8 are both predicted to leave the target word occupying around 20-22% of the spectro-
176 temporal plane, yet the BMN1 masker results in a far larger lexical frequency effect.

177 4. Discussion

178 In two extensive corpora, misperceptions reported by listeners were words of a higher lexi-
179 cal frequency than their corresponding intended target words. Lexical frequency difference
180 shows an apparent dependence on the type of masker, being substantially larger for three
181 pure energetic maskers than two babble maskers (Fig. 1), but some of the effect may be due
182 to differences in the amount of acoustic information which survives masking according to a
183 glimpsing model (Fig. 2). This outcome supports the finding of an increased lexical frequency
184 effect at lower SNRs⁷. It is conceivable that increased acoustic uncertainty favours the use of
185 word frequency priors. An example from the EN dataset illustrates this possibility: “clinic”
186 with a lexical frequency of 3.9 Zipfs was misperceived as “finish” (5.1 Zipfs) in the presence
187 of the SSN masker, perhaps due to the masker eroding acoustic-phonetic information for
188 the target word apart from evidence for the two vowel nuclei, leaving listeners to hypothe-
189 sise a word with the corresponding vowels. In such situations, one would anticipate lexical
190 frequency having a role in the choice of word to report. If lexical frequency is more likely
191 to come into play in more adverse masking conditions, the absence of a frequency effect for
192 naturalistic word misperceptions⁶ may be due to the environment under which mispercep-

193 tions occurred being insufficiently adverse to engage prior lexical frequency information in
194 the process of deciding which word was heard.

195 However, a comparison of Figs. 1 and 2 suggests that something more than pure ener-
196 getic masking is needed to fully explain the role of lexical frequency in word misperceptions.
197 One possibility is that the additional acoustic-phonetic information contributed by an in-
198 formational masker acts as a source of constraint on possible word hypotheses, which in
199 turn limits or eliminates a role for lexical frequency. This notion can be illustrated with an
200 example from the EN dataset: target word “wife” (5.2 Zipfs) was misperceived in BAB4 for
201 the less frequent word “twice” (4.8 Zipfs); an inspection of the words making up the babble
202 provides clear evidence for a word-initial /t/ and a word-final /s/ with a temporal alignment
203 appropriate for their incorporation in the reported word. Here, the ability to fit alterna-
204 tive word candidates is constrained by elements in the babble, attenuating the influence of
205 lexical frequency. The limited room for manoeuvre in the presence of additional phonetic
206 cues contrasts with the uncertainty created in the face of missing information due to pure
207 energetic masking. Further support for this hypothesis awaits a detailed examination of
208 each individual misperception in the context of the acoustic information of the babble signal
209 which elicited the misperception.

210 The reduced lexical frequency effect for our 4- and 8-talker babble maskers for SNRs
211 below 0 dB is at odds with the findings of Felty et al.⁹, who reported a lexical frequency effect
212 for a 6-talker babble masker for SNRs in the range 0-10 dB. However, there are differences in
213 both the speech and masker materials and the elicitation techniques used in the two studies.

214 Perhaps the biggest disparity is in the mean lexical frequency of the target words. Using the
215 US subtitle-based lexical frequency data¹⁸, we calculated the mean Zipf value for the target
216 words of Felty et al. to be 3.16 Zipfs, a value substantially lower than the mean of around
217 4.2 Zipfs for the datasets of the current study. Since low frequency targets are *a priori* more
218 likely to result in higher frequency responses than targets of a higher mean lexical frequency,
219 it is understandable that Felty et al.⁹ observed a lexical frequency effect at higher SNRs than
220 those used in the current study. A further difference between the two studies is the nature
221 of the speech material making up the babble. In Felty et al.⁹ the masking material came
222 from a different talker than that of the target words, while in the current study the target
223 talker could also appear in the babble. Informational masking effects are thus expected to
224 be higher for our stimuli, and as a consequence it seems likely that speech fragments from
225 the masker were more easily misallocated into the final word misperception.

226 The structure of English and Spanish differs in many respects, including vowel inventory
227 size (greater for EN), inflectional morphology (richer for SP), and presence of consonant
228 clusters (greater for EN). In spite of these differences, the similar across-masker patterning of
229 lexical frequency effects for the two languages suggests that relatively low-level processes such
230 as energetic masking and misallocation of acoustic-phonetic evidence from the masker can
231 modulate the extent to which lexical frequency priors are engaged during word recognition.

232 5. Conclusions

233 Across five types of masker and two languages, listeners reported words of a higher lexical
234 frequency than the intended target words. The size of the lexical frequency effect was

235 larger for pure energetic maskers than for maskers containing speech. However, the pure
236 energetic maskers of the current study possessed a greater predicted masking potential than
237 the babble maskers, suggesting that lexical frequency has more influence when acoustic-
238 phonetic information is scarce. The role of lexical frequency might be reduced in the presence
239 of a speech-based masker, by limiting the number of lexical hypotheses compatible with
240 audible acoustic-phonetic evidence from both target and masker.

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