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Phonological Symmetry Does Not Predict Generalization of Perceptual Adaptation to Vowels

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Abstract

Speech perception is inherently adaptive, with context-dependent rather than fixed perceptual phoneme boundaries. Exposure to novel vowel variants in lexically biasing contexts induces lasting boundary shifts toward the novel variant. Studies have found mixed results as to whether perceptual adaptation generalizes to phonologically related vowels and suggest that phonological symmetry might predict generalization. We test this hypothesis in Turkish, which has a fully symmetrical 8-vowel inventory. Listeners were exposed to words with either lowered /i/s or raised /ɛ/s and identified vowels on /i-e/ and /u-o/ continua to assess perceptual adaptation and generalization. We found perceptual adaptation to only lowered /i/s in /i-e/ identification and no generalization of perceptual adaptation in /u-o/ identification. We argue that phonological symmetry might not be sufficient for generalization, and that vowel inventory size and organization might also play a role.

Index Terms: speech perception, lexically guided perceptual adaptation, perceptual generalization, vowel perception

1. Introduction

Variation in speech requires speech perception to be adaptive. Phonemes do not manifest identically across situations, such as different phonetic contexts, and neither are listeners' perceptual phoneme boundaries fixed across situations. Influential work has shown that the same ambiguous stop sound from a /d-t/ continuum may be perceived as /d/ in a *dash-tash* continuum, but as /t/ in a *task-dask* continuum, which can be described as a 'lexicality' effect [1]. The lexically guided perceptual adaptation paradigm introduced by [2] makes use of lexicality effects to induce adaptation that persist beyond the specific lexical instances in which the effect is observed. [2] show that when listeners are exposed to novel variants of a phoneme embedded in lexical contexts that bias their perception, listeners' previously learned perceptual phoneme boundaries shift in the direction of novel variants following exposure. For example, in a study testing perceptual adaptation with vowels, [3] exposed Dutch listeners to words in which either /i/s or /e/s are replaced by a vowel [?] that is ambiguous between /i/ and /e/ in a lexical decision task (e.g., [hɑrmon?] where /hɑrmoni/ is a word but /hɑrmone/ is not). In other words, listeners heard exposure words with either lowered /i/s (encroaching on the acoustic space of /e/, such as [hɑrmon?] instead of [hɑrmoni]) or raised /e/s (encroaching on /i/, such as [vɛrk?r] instead of [vɛrker]) relative to more canonical pronunciations of these words. Following exposure, listeners who were exposed to words with lowered /i/s identified more steps of an /i-e/ continuum as /i/ compared to listeners who were exposed to words with raised /e/s, suggesting that listeners lowered or raised their perceptual phoneme boundary between /i/ and /e/ toward the novel variant they were exposed to. What is not yet clear is whether perceptual adaptation in vowels is specific to the phonemes listeners were exposed to (e.g., /i/ and /e/, in [3]) or if listeners generalize the shift to phonologically related phoneme contrasts not presented in exposure trials (e.g., /u/ and /o/, with the same example).

Testing whether exposure to lowered or raised front vowels initiates perceptual adaptation that generalizes to back vowel identification in Dutch and English, [3] and [4] find adaptation to front vowels with evidence of boundary shifts between /i/ and /e/ or endorsement of novel words with lowered front vowels, but mixed results for generalization of perceptual adaptation to novel back vowels, such as /ɔ/ and /ɑ/ or /u/ and /o/. In contrast, [5] find that Greek listeners lower or raise their perceptual boundary between /i/ and /e/ following exposure to lowered /i/s or raised /e/s, and generalize the shift to their perceptual boundary between /u/ and /o/ without exposure to lowered or raised variants of these vowels. [5] argue that generalization is facilitated by the phonologically symmetrical 5-vowel inventory of Greek (consisting of high front /i/, mid front /e/, low central /a/, mid back /o/, and high back /u/) where phonological similarities across vowels might be more salient than in Dutch or English, whose vowel systems require a greater number of specified features. Alternatively, generalization might have been facilitated by the smaller size of the 5-vowel Greek inventory in contrast to the larger inventories of Dutch and English. The present study aims to replicate [5] in Turkish to test whether phonological symmetry predicts generalization of perceptual adaptation to vowels.

The Turkish vowel inventory consists of 8 phonemic vowels, /ɑ e ɯ i o œ u y/ and is fully symmetric with respect to three binary feature contrasts: front/back, round/unround, and high/nonhigh (Table 1). The phonological description of the vowel inventory stems from two types of vowel harmony that are active in Turkish: backness harmony and rounding harmony, which involve word-internal agreement in backness and rounding, respectively [6]. All 8 Turkish vowels participate in backness harmony as targets and triggers, but whereas all 8 vowels participate in rounding harmony as triggers, only the four high vowels are targets for rounding harmony. The 8 vowel phonemes also have a number of allophones. Of interest here is that the front unround nonhigh vowel /e/ has two allophones, occurring as the open-mid [ɛ] allophone in noninitial syllables and as the close-mid [e] allophone in initial syllables [7].

Compared to the vowel inventory of Greek, the Turkish vowel inventory is larger but also arguably more phonologically symmetrical, and hence is suitable to test whether phonological symmetry predicts generalization of

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perceptual adaptation. Following [5], we exposed native Turkish listeners to either lowered /i/s or raised /ɛ/s in lexically biasing contexts, and then tested their vowel identification on /i-e/ and /u-o/ continua. Perceptual adaptation was measured via within-subjects comparisons of perceptual phoneme boundaries assessed prior to and following exposure. Based on [5]'s argument that phonological symmetry facilitates generalization of lexically guided perceptual adaptation to vowels, and considering Turkish has vowel harmony processes that potentially make the phonological symmetry of vowels even more salient, we hypothesized that perceptual adaptation would generalize from the exposure vowels to the generalization vowels in Turkish.

Table 1: *Turkish vowel inventory.*

	front		back	
	unround	**round**	**unround**	**round**
high	i	y	ɯ	u
nonhigh	e ([ɛ])	œ	ɑ	o

2. Methods

2.1. Participants

Participants were 20 monolingually raised, fluent, and native speakers of Turkish with normal hearing. Because remote participant recruitment services for experimental procedures are not available in Turkey, participants were recruited remotely from Prolific's UK and Germany participant pools. All participants were fluent in English and had been living in their respective countries of residence for 2 to 9 years.

2.2. Stimuli

2.2.1. Vowel identification stimuli

Vowel identification stimuli consisted of two sets of 10-step continua, /bit-bet/ and /but-bot/, where the endpoint tokens are Turkish words. The steps consist of psychoacoustically equidistant, formant resynthesized vowel tokens embedded in a roundness-matched [bVt] context. To create the 10-step /i-e/ and /u-o/ continua, the first 4 formants and associated bandwidths of an /i/ vowel token produced by the first author, a native speaker of Turkish, were resynthesized using source-filter resynthesis formulae in Praat [8] and following [9] to calculate the bandwidths. Following [10], portions of the source vowels below 120 Hz and above 5500 Hz were restored after resynthesis, for increased auditory naturalness. Mean F1-F4 formant values of the resynthesized vowel tokens were estimated by the Burg method to monitor resynthesis results, and the filter formant values in the formulae were modified where necessary to reach intended resynthesized formant values. The mean F1-F4 formant values of the endpoint tokens are shown in Table 2. The intermediary steps which are omitted here had linearly interpolated formant values on the Bark scale.

Table 2: *Mean F1-F4 values of endpoint vowel tokens.*

Vowel token	F1	F2	F3	F4
/i/	351 Hz	2352 Hz	3194 Hz	3921 Hz
/e/	675 Hz	1787 Hz	2589 Hz	3921 Hz
/u/	351 Hz	1000 Hz	2800 Hz	4070 Hz
/o/	675 Hz	750 Hz	2800 Hz	4070 Hz

2.2.2. Exposure stimuli

Exposure stimuli were auditorily presented in a lexical decision task and consisted of Turkish words and nonwords in two experimental vowel height manipulation conditions, lowered /i/ and raised /ɛ/. Exposure stimuli were created from two lists of 96 items of [(C)V_1(C).CV_2(C)] structure, including 48 Turkish words and 48 Turkish nonwords, each consisting of 24 critical items and 24 filler items. All items contained only the Turkish front vowels. In critical words, the V_1 and V_2 vowels were either /i/ or /e/. In order to not interfere with the vowel height manipulation, filler words for the lowered /i/ condition contained only the nonhigh front vowels /e, œ/, whereas filler words for the raised /ɛ/ condition contained only high front vowels /i, y/. All items were naturally produced and recorded by the first author. Resynthesized vowels were then spliced into the recorded items to replace the naturally produced vowels.

In filler words and nonwords, resynthesized vowel tokens were unambiguous and phonemically identical with the vowels they replaced. Critical words of the lowered /i/ condition are illustrated by the Turkish word /cedi/ (*cat*), whose lexical specification has an /e/ as V1 and /i/ as V2. In these words, splicing was used to replace V1 with an unambiguous [e] token and V2 with [?i], a vowel that is perceptually ambiguous between /i/ and /ɛ/. Critical words of the raised /ɛ/ condition are illustrated by the Turkish word /tibɛt/ (*Tibet*), whose lexical specification has an /i/ as V1 and /ɛ/ as V2. In these words, splicing was used to replace V1 with an unambiguous [i] token and V2 with [?ɛ], a vowel that is perceptually ambiguous between /i/ and /ɛ/. (The perceptually ambiguous vowel quality was determined in an independent norming experiment.) [1] Critical nonwords were created in a similar manner, with the V_1 vowel replaced by an unambiguous [e] and V_2 vowel replaced by a vowel token [?i] in the lowered /i/ condition, and the V_1 vowel replaced by an unambiguous [i] and V_2 vowel replaced by a vowel token [?ɛ] in the raised /ɛ/ condition, but in both cases, the result is a nonword whether the ambiguous vowel is interpreted as /i/ or /ɛ/. Replacing the V_2 vowels of the critical words with any Turkish vowel other than the lexically specified vowel resulted in a nonword, and hence the lexical context should bias the perception of the ambiguous vowel tokens toward the lexically specified /i/ or /ɛ/. However, the resulting lexically biased percepts would be a lowered (and backed) /i/ in the case of [?i] and a raised (and fronted) /ɛ/ in the case of [?ɛ], relative to more canonical and unambiguous productions of the lexically specified vowels /i/ and /ɛ/, respectively (see Table 3). To ensure that listeners paid attention to vowels and did not base their judgements in the lexical decision task on consonantal frames only, 4 of the filler nonwords in each

[1] The ambiguous vowel tokens [?i] and [?ɛ] were resynthesized based on a pretest in which 8 native Turkish listeners performed vowel identification on the second vowels of 10-step /tepsi-tepsɛ/ and /pipit-pipɛt/ continua, where the 10-step /i-e/ continuum described in the previous section was spliced into naturally produced Turkish words /tepsi/ and /pipɛt/, and the F1-F3 formants of the perceptual boundaries in each continuum were fed into the resynthesis formulae of the respective ambiguous vowel tokens.

condition were created by replacing a vowel in a Turkish word with another vowel.

Table 3: *Mean F1-F4 values of V_1 and V_2 /i/ and /e/ vowel tokens.*

Vowel token	F1	F2	F3	F4
V_1 /i/	348 Hz	2370 Hz	3210 Hz	4025 Hz
V_1 /e/	600 Hz	1900 Hz	2700 Hz	3921 Hz
V_2 /i/	351 Hz	2352 Hz	3194 Hz	3921 Hz
V_2 /ɛ/	675 Hz	1787 Hz	2589 Hz	3921 Hz
V_2 [?i]	481 Hz	2105 Hz	2926 Hz	3921 Hz
V_2 [?ɛ]	518 Hz	2041 Hz	2857 Hz	3921 Hz

2.2.3. Procedure

The experiment consisted of a baseline vowel identification task followed by the lexical decision task (exposure phase) and lastly a vowel identification task (test phase). The vowel identification tasks in baseline and test phases were identical and contained the 10-step /bit-bet/ and /but-bot/ continua in two separate blocks with three repetitions of each continuum. In each trial, participants were presented with a random token from the 10-step /bit-bet/ or /but-bot/ continua and were asked to indicate in a 2-alternative forced choice design whether the word they heard was "*bit*" or "*bet*," or "*but*" or "*bot*".

In the lexical decision task, participants were either assigned to the lowered /i/ condition or the raised /ɛ/ condition and were presented the relevant set of stimuli accordingly. In each trial, participants were presented with a randomly selected word or nonword and were asked to indicate in a 2-alternative forced choice design whether the stimulus they heard was a Turkish word or not. Participants first completed 8 practice trials (2 critical words with ambiguous V_2, 2 critical nonwords with ambiguous V_2, 2 filler words, 2 filler nonwords; practice stimuli were a separate set of stimuli created following the same methods described above for creating exposure stimuli). Following a response, each trial concluded with feedback about the lexical status of the stimulus, which explicitly identified the critical items with ambiguous V_2 as words to enhance the lexically-biased lowered /i/ or lowered /e/ perception. In the exposure phase, participants performed the same task over the full set of 96 stimuli presented twice, without receiving feedback. Participants were not informed that they would hear ambiguous vowel tokens in this task.

3. Results

Data from 2 participants who did not reach 70% accuracy in the lexical decision task were excluded. For the remaining participants, average accuracy in critical word trials of the lexical decision task was 83.1%, indicating that listeners perceptually accommodated the ambiguous vowels under lexical guidance.

To examine whether participants shifted their perceptual boundaries after exposure to lexically biased ambiguous vowel tokens and generalized this behavior to novel vowels, participants' vowel identification in baseline and test were compared. First, participants' perceptual boundaries in /i-e/ and /u-o/ continua in baseline and test were calculated by modeling participant responses with continuum step F1 as the predictor variable, where the perceptual boundary is the F1 value at which a participant's predicted probability of an /i/ or /e/ response is 0.5. To be able to compute estimates in cases of perfect separation in which participant responses along a continuum crossed over from 100% high vowel responses to 100% nonhigh vowel responses with no intermediary responses, in which cases the slope of the identification function is infinite, bias-reduced binomial generalized linear modeling [11] was used to model all data. For five participants, a perceptual boundary at which participant responses crossed over from /u/ to /o/ within the continuum steps could not be identified due to the lower endpoint of the continuum not being perceived as /o/ unambiguously. The /u-o/ responses of these participants were excluded from further analyses. All remaining participants identified both endpoints as /u/ and /o/ unambiguously as intended, with several participants exhibiting perfect separation in their /u-o/ identification, confirming the validity of the /u-o/ continuum. By-participant vowel identification boundaries were fit to a linear mixed-effects model [12] with vowel continuum (/i-e/ vs. /u-o/), block (baseline vs. test), condition (lowered /i/ vs. raised /ɛ/), and their interactions as independent variables, and by-participant random intercepts (block and vowel continuum were not included as by-participant random slopes due to convergence issues). There was a marginally significant interaction of block and condition ($\beta = -5.35$, $SE = 2.91$, $t = -1.84$, $p = 0.07$). Post-hoc tests revealed that in the lowered /i/ condition, participants' perceptual boundaries were lower in test (497.49 Hz) compared to baseline (478.11 Hz, $p = 0.03$) collapsing across the /i-e/ and /u-o/ vowel continua. No significant boundary shift was found from baseline (498.89 Hz) to test (500.86 Hz) in the raised /ɛ/ condition ($p = 0.83$).

A second, more in-depth examination of the vowel identification data was conducted, analyzing participant responses in full rather than reduced to the F1 value at the perceptual boundary (which led to convergence issues). In this analysis, responses were modeled (Figure 1) as the dependent variable in a mixed- effects logistic regression model with vowel continuum (/i-e/ vs. /u-o/), block (baseline vs. post-exposure), condition (lowered /i/ vs. raised /ɛ/), and their interactions, and continuum step (F1) as independent variables; and with by-participant random intercepts and vowel continuum and order as by-participant random slopes (test block was not included as a random slope due to convergence issues). There was a significant main effect of continuum step ($\beta = -6.27$, $SE = 0.4$, $z = -15.64$, $p < 0.0001$) such that higher F1 yielded less high vowel responses (/i/ or /u/, depending on the continua). There was a marginally significant interaction of block and condition ($\beta = -0.32$, $SE = 0.18$, $z = -1.81$, $p = 0.06$). Post-hoc tests revealed that collapsing across vowel continua, there was a greater probability of high vowel responses in test (0.26) than in baseline (0.09, $p = 0.02$) in the lowered /i/ condition, whereas no difference between baseline (0.31) and test (0.29) was found in the raised /ɛ/ condition ($p = 0.83$). This finding replicates the result from the linear model of the perceptual boundaries. However, this interaction was qualified by a marginally significant interaction of vowel continuum, block, and condition ($\beta = 0.22$, $SE = 0.12$, $z = 1.82$, $p = 0.07$). Post-hoc tests revealed that in the lowered /i/ condition, there was a greater probability of high vowel responses to the /i-e/ continuum in test (0.37) than in baseline (0.12, $p = 0.02$), whereas no significant difference was found for the /u-o/ continuum between baseline (0.08) and test (0.19, $p = 0.12$) or in the raised /ɛ/ condition (ps > 0.16).

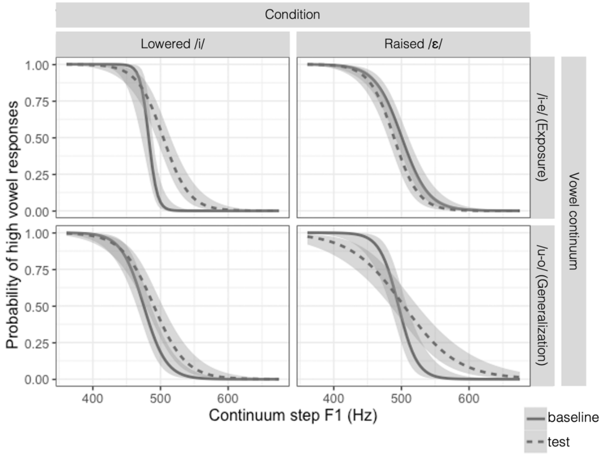

Figure 1: *Vowel identification results.*

4. Discussion

The lexically guided perceptual adaptation paradigm rests on (i) the endorsement of novel variants during exposure and (ii) persistent, post-exposure boundary shifts that are in line with the lexically biased perception in exposure. In the present study, participants endorsed more than 80% of the ambiguous vowels they heard under lexical bias in the lexical decision task, indicating perceptual accommodation to the novel, ambiguous vowels they were exposed to. If this perceptual accommodation resulted in perceptual adaptation beyond the exposure phase, we should find a significant interaction of condition and block as predictors of vowel identification responses, whereby participants in the lowered /i/ condition are expected to have lower boundaries in test than in baseline whereas participants in the raised /ɛ/ condition are expected to have higher boundaries in test than in baseline. In both models of perceptual boundaries and vowel identification responses, the interaction of condition and block were marginally significant. However, the planned post-hoc comparisons provided evidence in support of perceptual adaptation in the lowered /i/ condition only, where participants had lower perceptual boundaries between high-nonhigh vowel pairs following exposure to words with lowered /i/s. On the other hand, no boundary shift was observed in the raised /ɛ/ condition, indicating that despite perceptually accommodating words with raised /ɛ/s in the lexical decision task, listeners did not recalibrate their perceptual boundaries following this lexically biasing exposure.

An explanation for why perceptual adaptation was observed in the lowered /i/ condition but not in the raised /ɛ/ condition might be that the nonhigh unrounded front vowel in Turkish, /e/, has two allophones that differ in height, [e] and [ɛ], and hence listeners' perceptual boundaries need not shift to accommodate the raised /ɛ/s they were exposed to. In contrast, the finding of boundary shift from baseline to test in the lowered /i/ condition is taken as evidence that listeners can and do update their perceptual boundaries following exposure to novel vowel variants. Moreover, with the effect observed within participants, this is stronger evidence for perceptual adaptation compared to prior studies which show adaptation only in vowel identification assessed at post-exposure across experimental conditions or relative to a control condition (e.g., [3], [5]). Previous studies ([13]; [4]) of lexically guided perceptual adaptation in vowels that had within-subjects assessment of boundary shifts involved exposure to *phonemic* vowel shifts mapping one phoneme onto another phoneme, such as words with /e/s replaced by /i/s. The present study is novel in the sense that we show in a within-subjects design that listeners recalibrate their perceptual boundaries after exposure to more subtle vowel formant manipulations that do not impact phonemic vowel identity but result in vowels that are are maximally ambiguous.

A major goal of this study was to replicate [5] in Turkish to examine generalization of perceptual adaptation to phonologically related vowels. [5] found a similar degree of perceptual adaptation in exposure vowels and generalization vowels. In the present study design, where boundary shifts were tested from baseline to test, a full replication of [5]'s results would involve a two-way interaction between condition and block, and no three-way interaction of condition, block, and vowel continuum indicating different degrees of perceptual adaptation for exposure vs. generalization vowels. However, in our model of the vowel identification responses, the marginally significant interaction of condition and block was qualified by a marginally significant interaction of condition, block, and vowel continuum. Moreover, planned post-hoc comparisons revealed no evidence in support of generalization of lexically guided perceptual adaptation in the lowered /i/ condition to the phonologically related /u-o/ contrast. Although the number of participants in [5] are not substantially higher, with 14 participants per condition, we acknowledge that the small number of participants in our study is a limitation.

[5] argue that the phonological symmetry of the Greek vowel inventory facilitated the generalization of perceptual adaptation to phonologically related vowels. Although the Turkish vowel inventory is also phonologically symmetrical, our results suggest that phonological symmetry might not be a sufficient condition for the generalization of perceptual adaptation in vowels. That our results do not replicate [5] might be attributed to the differences in the sizes and organizations of the vowel inventories of Greek compared to Turkish. The size of the vowel inventory might be a stronger predictor of generalization of perceptual adaptation, with the 5-vowel inventory of Greek facilitating generalization but not the larger vowel inventories of Turkish, English, and Dutch. Another consideration is that, whereas there are no intervening vowels between the exposure and generalization vowels in the Greek vowel inventory (i.e., no vowel in the acoustic space between /i/ and /u/ or /e/ and /o/), the exposure and generalization vowels in the Turkish vowel inventory were separated by two intervening vowels, i.e., /y/ and /ɯ/ in the case of /i/ and /u/, and /œ/ and /ɑ/ in the case of /e/ and /o/. However, our findings also don't agree with [3], who found that generalization of perceptual adaptation to phonetically and phonologically distant but not near vowels were facilitated in Dutch. Hence, our results are inconclusive with respect to the question of phonological symmetry, and future research might clarify the results here.

5. Conclusions

The main goal of this study was to examine generalization of perceptual adaptation in vowels in Turkish, yet we did not observe any evidence in support of generalization. Nonetheless, our experimental design provides evidence in support of lexically guided perceptual adaptation in vowels by identifying boundary shifts following exposure to ambiguous vowel tokens in a within-subjects design relative to baseline perceptual boundaries assessed prior to exposure.

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7. References

[1] W. F. Ganong, "Phonetic categorization in auditory word perception," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 6, no. 1, pp. 110–125, 1980. [Online]. Available: https://doi.org/10.1037/0096-1523.6.1.110

[2] D. Norris, J. M. McQueen, and A. Cutler, "Perceptual learning in speech," *Cognitive Psychology*, vol. 47, no. 2, pp. 204–238, 2003. [Online]. Available: https://doi.org/10.1016/S0010-0285(03)00006-9

[3] J. M. McQueen and H. Mitterer, "Lexically-driven perceptual adjustments of vowel categories," in *Proceedings of the ISCA Workshop on Plasticity in Speech Perception*, 2005, pp. 233–236.

[4] J. Maye, R. N. Aslin, and M. K. Tanenhaus, "The weckud wetch of the wast: Lexical adaptation to a novel accent," *Cognitive Science*, vol. 32, no. 3, pp. 543–562, 2008. [Online]. Available: https://doi.org/10.1080/03640210802035357

[5] K. Chládková, V. J. Podlipskỳ, and A. Chionidou, "Perceptual adaptation of vowels generalizes across the phonology and does not require local context," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 43, no. 2, pp. 414–427, 2017. [Online]. Available: https://doi.org/10.1037/xhp0000333

[6] B. Kabak, "Turkish vowel harmony," *The Blackwell Companion to Phonology*, pp. 1–24, 2011. [Online]. Available: https://doi.org/10.1002/9781444335262.wbctp0118

[7] İ. Ergenç and İ. P. B. Uzun, "Türkçenin ses dizgesi," Ankara, Turkey: Seçkin Yayıncılık, 2017.

[8] P. Boersma and D. Weenink, "Praat: doing phonetics by computer [Computer program]," Version 6.3.10. [Online]. Available: http://www.praat.org/. Accessed on: May 3, 2023.

[9] J. W. Hawks and J. D. Miller, "A formant bandwidth estimation procedure for vowel synthesis," *The Journal of the Acoustical Society of America*, vol. 97, no. 2, pp. 1343-1344, 1995.

[10] M. B. Winn, "GUI-Based Wizard for Creating Realistic Vowel Formant Continua from Modified Natural Speech," Version 43, 2023. [Online]. Available: https://www.mattwinn.com/praat/Make_Formant_Continuum_v44.txt. Accessed on: May 3, 2023.

[11] I. Kosmidis, "brglm: Bias Reduction in Binomial-Response Generalized Linear Models," R package version 0.7.2. [Online]. Available: https://github.com/ikosmidis/brglm. Accessed on: Jan. 2021.

[12] D. Bates, M. Maechler, B. Bolker, and S. Walker, "Fitting Linear Mixed-Effects Models Using lme4," *Journal of Statistical Software*, vol. 67, no. 1, pp. 1–48, 2015.

[13] E. Felker, M. Ernestus, and M. Broersma, "Lexically guided perceptual learning of a vowel shift in an interactive L2 listening context," in Proceedings of Interspeech 2019, 2019, pp. 3123–3127. [Online]. Available: https://doi.org/10.21437/Interspeech.2019-1414