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An Acoustic Analysis of Surrounding Vowel Effects on Intervocalic /h/ in Turkish

Türkçede Ünlülerarası /h/ Üzerine Çevresel Ünlülerin Akustik Etkilerinin Çözümlemesi

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Abstract

Previous studies on Turkish glottal consonant /h/ typically investigated the acoustic characteristics of this consonant; however, recent studies generally examine the formant frequency changes between preceding and following vowels as to determine the place of articulation of fricatives. This study investigates the place of articulation of Turkish /h/ in intervocalic position by comparing formant frequency changes of preceding and following vowels through their height and rounding characteristics of vowels. A production experiment is conducted with 21 speakers in a sound-proof booth. Stimuli consisted of eight Turkish vowels in preceding and following positions of intervocalic /h/ embedded into a carrier sentence (e.g., [Adam tohum yazdı] 'The man seed write -past'). Rawdata analysis was performed on normalized mean F1, F2, F3, F2_3 values of each vowel adjacent to /h/. Findings for preceding vowels showed a decrease in rounding features of mean F1, F2, F3 and F2_3 values. On contrary to preceding vowels, findings for the following vowels indicated an increase in both height and rounding features for the mean F1 and F2 values. Overall results suggested that formant changes on the following vowels elicited more significance for the acoustic changes in following vowels compared to preceding vowels.

Keywords: Formant, normalization, intervocalic, production, acoustics.

Öz

Türkçede gırtlaksıl /h/ ünsüzü üzerine yapılan önceki çalışmalar bu ünsüzün akustik özelliklerini incelemektedir. Ancak, güncel çalışmalarda sürtünücülerin çıkış yerini belirlemek için genellikle sürtünücünün öncülünde ve ardılında konumlanan ünlülerin formant sıklık değişimleri araştırılmaktadır. Bu çalışma, ünlülerarası konumdaki /h/ ünsüzünün öncülündeki ve ardılındaki ünlülerin formant değerlerindeki değişimleri kıyaslayarak, ünlülerin yükseklik ve yuvarlaklaşma özellikleri bağlamında /h/ ünsüzünün çıkış yeri özelliğini incelemektedir. Sesletim deneyi, 21 konuşur ile ses yalıtımlı kabinde gerçekleştirilmiştir. Uyaranlar, Türkçe ses dizgesindeki sekiz ünlü /h/ ünsüzünün öncülünde ve ardılında konumlanacak biçimde taşıyıcı tümce içerisine yerleştirilmiştir ([Adam tohum yazdı]). Hamveri analizleri /h/ ünsüzünün ses çevresinde bulunan her bir ünlünün normalize edilmiş ortalama F1, F2, F3 ve F2_3 değerleri üzerinde gerçekleştirilmiştir. Öncül ünlülerin bulguları, ortalama F1, F2, F3 ve F2_3 değerlerinde yuvarlaklaşmayla düşüş olduğunu göstermiştir. Öncül ünlülerin aksine, ardıl ünlülerin bulguları hem yükseklik hem yuvarlaklaşmayla

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ortalama F1 ve F2 değerlerinde yükselme olduğunu belirtmiştir. Genel olarak, sonuçlar ardıl ünlülerin akustik özelliklerinin değişiminin öncül ünlülere kıyasla daha anlamlı olduğunu ortaya koymuştur.
Anahtar sözcükler: Formant, normalizasyon, ünlülerarası, üretim, akustik.

Introduction

The consonant /h/ is defined as voiceless in regard to vibration of vocal cords, glottal in terms of place of articulation and fricative with respect to manner of articulation in acoustic phonetics. Previous studies have been suggested different observations in theoretical (see Chomsky & Halle, 1968; Roach, 1983; Keating, 1988; Laufer, 1991; Maddieson, 1984; Brinton, 2000; Fant, 2005; Skandera & Burleigh, 2005; Gussenhoven & Jacobs, 2011; Knight, 2012; Zsiga, 2013; Davenport & Hannahs, 2020) and experimental (see Laufer, 1991; Wright, Hargus & Miller, 2005; Sun, Yu & Jin, 2014; Pandey, Mahesh & Dutta, 2017; Malik & Kokub, 2020) studies. In line with these studies, the consonant /h/ is generally defined as a voiceless, glottal and fricative.

The phonetics of Turkish glottal /h/ are well-described in background studies largely on glottal fricative (see Selen, 1979; Aksan, 1980; Sezer, 1986; Mielke, 2002; Ergenç & Uzun, 2020), glottal approximant (see Kornfilt, 1997), and voiceless counterpart of adjacent vowel (see Ertan, 2013). A limited number of studies have made remarkable contributions to Turkish phonetics by providing important knowledge on /h/. However, these studies generally involve small sample groups of participants, and they mainly focused on the spectral aspects of this consonant. While one area where our understanding lags behind is the effect of extensive sample groups, and another area is the need of detailed analysis of acoustic characteristics of /h/ in Turkish. From this point, the main purpose of the present study is to investigate the acoustic parameters of preceding and following vowels intervocalic positioned /h/ in Turkish by using a large sample group of participants. Vowels positioned before and after /h/ were examined by their height and rounding features through formant frequencies. Acoustic parameters used in the study are mean F1, F2, F3, and F2_3 formant frequencies.

The paper is structured as follows: The next subsections will provide background information on acoustic characteristics of glottal /h/ in Turkish and formants. In the Section 2, we summarize the production experiment, methodology, and statistical analysis. In the Section 3, we provide the findings on the acoustic correlates of preceding and following vowels in intervocalic position of glottal /h/ consonant in Turkish. In the last section, we briefly summarize the findings and discuss our research questions in the light of findings and overall results.

Phonemic and phonetic characteristics of /h/

The glottal /h/ is phonemically defined by the glottal place of articulation at vocal cords level. This consonant is generally accepted as fricative and voiceless in many languages (see Chomsky & Halle, 1968; Gussenhoven & Jacobs, 2011; Ladefoged & Disner, 2012). The acoustic characteristics and its' presence can vary according to allophonic differences and dialect-specific variations between languages. For instance, the English words *hat* and *at* indicate the phonemic differences of glottal /h/ in that language. There are many different views on the description of this consonant in previous works. For instance, Ladefoged and Disner (2012) discussed the phonemic features of consonant /h/ in this context. According to their point of view, researchers referred /h/ a glottal fricative consonant because of the slight noise above the vocal cords when producing /h/. Roach (1983) proposed that consonant /h/ tends to bare the phonemic features of its preceding vowel when it is compared to following vowel. From a similar perspective, Collins and Mees (2003) suggested that to produce /h/, the articulators shape the vocal tract similar to the following vowel. By this way, it generates a strong friction between the vocal cords and vocal tract which makes the consonant /h/ a voiceless vowel. Ladefoged and Disner provided an additional contribution on the interpretation of glottal and fricative /h/ consonant. They stated that the noise produced by this consonant is not directly related to air passing through a narrow gap in the vocal tract. Instead, it comes from the air movements along the edges of the open vocal cords and different surfaces of the vocal tract. That is the reason why researchers called /h/ as a noisy vowel rather than a fricative consonant. Previous works (see

Chomsky & Halle, 1968; Gussenhoven & Jacobs, 2011) also hypothesized this view by referring /h/ a semivowel since this sound does not directly have the exact characteristics of both consonants and vowels.

These studies indicate that /h/ generates a turbulent noise due to the constricted airflow at the glottis and this phonetically makes a characteristic of fricative sound. However, the turbulence of the production covers a wide range of formant frequencies which makes /h/ acoustically diffuse. Therefore, the acoustic features of this sound can be influenced by the surrounding vowels that result in different formant transitions. This is one of the most remarkable motivations of our current study. According to our point of view, the formant transitions between surrounding vowels (preceding and following) in Turkish may reflect the shape of vocal tract during the production of the neighboring vowels.

There are different points on glottal fricative /h/ which exhibits a wide range of acoustic features across languages. On one hand, it is phonetically accepted as a typically voiceless sound and influenced by the surrounding vowels, on the other hand, it phonemically serves a distinctive sound with different roles. For instance, Keating (1988) expressed a contrasting view to argumentations about /h/ being a semi-vowel. Keating stated that /h/ is produced by direct articulation between vocal cords, instead of acquiring the characteristics of the following vowel. Therefore, /h/ is a glottal and approximant consonant, not a semivowel. On the other hand, Laver (1994) stated that /h/ can be classified as whispered or breathed approximant sound since the open vocal tract is narrowed during the production. Brinton (2000) also supported the surrounding vowel debates by examining the following vowel of /h/ and describing /h/ a voiceless, glottal, and approximant sound.

Contrary to previous works, Laufer (1991) discussed that the sound /h/ could be classified as a glottal fricative in the IPA chart rather than a voiceless vowel or an approximant consonant. Laufer refers that even though the vocal tract is completely opened during the production, the narrowest part has a space between the vocal cords. That is why any friction could be heard during production. Later, Maddieson (1984) suggested that the weak friction heard with voiceless /h/ is caused by turbulence, making /h/ a weak fricative, not an approximant. Similarly, Fant (2005) stated that /h/ has weak consonant characteristics, but it is not a vowel since it is less vowel-like. However, Skandera and Burleigh (2005) proposed a different view, claiming that /h/ is produced without obstruction in the vocal tract and thus it is a cavity fricative.

Theoretical approaches cited above are investigated in the experimental studies by examining formant transitions and spectrographic features of /h/ in between surrounding vowels environments. One of the first experimental work of Laufer (1991) observed the vocal cords during production of /h/ using imaging experiment. Laufer referred that the friction is not different from other fricative sounds except for the place of articulation since the vibrations of following vowels continued during production. From this context, previous works also supported that the spectrographic patterns of /h/ are similar formant patterns with vowels, and this makes sound /h/ having more intensity in the formant transitions than other fricative consonants (Wright et al., 2005; Sun et al., 2014; Malik & Kokub, 2020). In the next section of this study, the phonemic and phonetic characteristics of sound /h/ in Turkish is discussed by using experimental studies.

Phonemic and phonetic accounts of /h/ in Turkish

Previous studies describing the phonemic and phonetic aspects of /h/ in standard Turkish generally classify this consonant as glottal, fricative, and voiceless (see Aksan, 1980; Selen, 1979; Mielke, 2002; Yavuz & Balcı, 2011; Ertan, 2013; Ergenç & Uzun, 2020). Accordingly, Turkish /h/ generally occurs as a glottal fricative in the word-initial (e.g., 'halı' *carpet*), intervocalically (e.g., 'saha' *area*), and word-final positions (e.g., 'fatih' *conqueror*). This phoneme exhibits allophonic differences according to phonological environment, which is particularly influenced by the adjacent vowels. Previous studies have generally defined /h/ as a glottal consonant directly reflecting the acoustic characteristics of the following and preceding vowels. Yavuz and Balcı also theoretically supported this view and redescribed the phonetic features of /h/. They stated that this glottal fricative is formed with the air passing through vocal cords without any obstruction. Turkish /h/ generally occurs in two different allophonic distributions depending on its acoustic environment. While the [x] appears as a velar fricative in back vowel environments (V[+back]_), which displays coarticulatory effects with the preceding vowel (e.g., 'kahve' *coffee*), the [ç] emerges as a palatal fricative in front vowel environments (V[+front]_), indicating phonetic assimilation to the context of the vowel (e.g., 'tehlike' *danger*) (see Selen, 1979; Mielke, 2002; Ertan, 2013; Ergenç & Uzun, 2020). Additionally, it is worth noting that there are different theoretical approaches to Turkish /h/ in the previous literature. In this regard, while Kornfilt (1997) classified Turkish /h/ as a central approximant, referring to /h/ as a semivowel, Hulst and Weijer (1991) describe two different phonological conditions for /h/, which tends to be deleted in various phonological environments. Based on this approach, if it is followed by a nasal in the syllable-final position or if it follows a vowel or a voiceless consonant in the syllable-initial position, /h/ might be deleted during production.

There are a limited number of remarkable acoustic studies on Turkish /h/, each addressing different research questions. One of the most leading studies of Mielke (2002) investigated /h/ in Turkish by using both production and off-line perception experiments. He found that an increase in energy density in F2 formant frequency corresponded with the allophone [ç] in front vowel environments; however, a decrease in energy density in F1 and F0 formant frequencies was related to the allophone [x] in back vowel environments. These phonetic surroundings have a significant impact on its acoustic properties, specifically that the consonant becomes less perceptually clear when it appears next to vowels that have low vibration and aperiodicity. These findings provided significant evidence on the acoustic characteristics of Turkish /h/ and its coarticulatory effects. Next, the acoustic study of Kılıç (2012) investigated the spectrographic patterns of /h/ by using intensity differences. He found that intensity values are similar to formant transitions of adjacent vowels of /h/ in Turkish. Another remarkable study of Ertan (2013) also discussed the spectrographic patterns of Turkish /h/ in different syllabic positions: word-initial, word-medial, and word-final positions. Accordingly, Ertan's production study demonstrated the basic acoustic features of /h/ in Turkish, which describes this consonant as the voiceless counterpart of the following vowel in the syllable-initial and the preceding vowel in the syllable-final positions. Her acoustic analysis indicated that /h/ in Turkish has similar formant patterns with surrounding vowels, specifically in syllable-initial position (e.g., 'hepten' *completely*). Ertan suggests that /h/ has the acoustic properties of the following vowel in syllable-initial position, while /h/ exhibits the acoustic characteristics of the preceding vowel in syllable-final position in Turkish (e.g., 'kahret-' *to curse*). These perspectives motivated us to investigate the acoustic characteristics of the Turkish vowels that appear preceding and following the intervocalic /h/ in Turkish, with an emphasis on how these surrounding vowels affect the formant frequencies across different phonological environments.

Formants and Formant Transitions

The frequency range of vibrations from the vocal cords identifies the fundamental frequency (F0) and other formant frequencies. As well known, formants are key features for the acoustic analysis of speech sounds and they are sourced by vibration in vocal cords through vocal tract (see Kent & Read, 2002; Gussenhoven & Jacobs, 2011; Zsiga, 2013; Davenport & Hannahs, 2020). Formants are interpreted as resonances through vocal tract; therefore, formants are generally accepted as the character of vocal tracts but not of sounds (Pickett, 1999; Stevens, 2000). These frequencies, which are specific to speech sounds, are called from frequency features of speaker's vocal tract: First formant frequency (F1, 500-1500 Hz), second formant frequency (F2, 1500-2500 Hz) and third formant frequency (F3, 2500-3500 Hz) (see Catford, 1988; Titze, 1994; Pickett, 1999; Hayward, 2000; Kent & Read, 2002; Johnson, 2003; Knight, 2012).

Each formant frequency is associated to an acoustic characteristic of vowels. For instance, F1 is related to tongue height in oral cavity, F2 is associated with backness of the tongue, and lastly F3 is related to vocal tract length and so with lip rounding. The frequency range of vibrations from the vocal cords sets the F0 and other formant frequencies which are significant for examining the speech sounds acoustically. When producing a vowel, a higher tongue position results in a low F1 (Kent & Read, 2002; Knight, 2012; Davenport & Hannahs, 2020) and the constriction in the front half of the mouth leads to a decrease in F1 (Gussenhoven & Jacobs, 2011; Odden, 2005). On the contrary, the constriction in the back half of the mouth causes an increase of F1 (Zsiga, 2013). For this reason, glottal constriction causes a rise in F1 values. On the other hand, F2 is generally related to the frontness and backness of the tongue in the oral cavity. Similar to F1, when producing a vowel, if the tongue is positioned in the back half of the mouth, F2 becomes low (Syrdal & Gopal, 1986; Flemming, 2002; Gussenhoven & Jacobs, 2011). However, when the tongue gets closer to front teeth, F2 becomes high (Brosnahan & Malmberg, 1979; Odden, 2005; Knight, 2012). Lastly, F3 is generally relevant to the length of the vocal tract and lip rounding. Lip rounding causes the lengthening of the oral tract and as a conclusion of lengthening, F3 decreases (Pickett, 1999; Kent & Read, 2002; Zsiga, 2013). One of the recent formant values of F2_3 represents the average of F2 and F3 frequencies. This calculation is developed by Xu and Gao (2013) to reduce the effect of dramatic formant shifts from F2 to F3 transitions. F2_3 modeling is mainly used as an acoustic parameter for formant analyses. Xu and Gao states if the calculation of F2_3 formula is more expedient than measuring F2 and F3 values separately is an empirical issue.

Formant transitions on spectrograms give acoustic information on where consonants are articulated during production. These transitions occur over the formant patterns of vowels that follow a consonant. Specifically, the F2 formant transition provides key insights into the place of articulation for fricatives (O'Connor, 1973). For example, the F2 value of a vowel following a consonant articulated at the back of the vocal tract is higher at the beginning of the vowel than the rest. When a high vowel follows a labial consonant, F2 of the vowel increases, but it decreases if the vowel is a back vowel. Similarly, F2 increases for a high vowel after an alveolar consonant but decreases if the vowel is a back vowel (see e.g., Mackay, 1978; Kent & Read, 2002; Davenport & Hannahs, 2020). Thus, the F2 formant transition of a vowel depends on the place of articulation of the adjacent consonant.

The present study

The following research questions are asked with respect to the aims of the present study: (i) How Turkish glottal fricative consonant /h/ affects normalized mean F1, F2, F3, and F2_3 formant frequency values of preceding and following vowels in intervocalic position? (ii) How can we interpret the changes in formant values with respect to height and roundness interaction? (iii) In extent of the effects on height and rounding characteristics of preceding and following vowels, how can we describe /h/ sound in this direction? In line with previous studies, we expect significant differences in the acoustic characteristics of mean F1 and F3 formant frequencies with respect to vowel height and roundness features. Accordingly, the production of the consonant /h/ in Turkish might represent significant different results for the vowels positioned before and after /h/ in intervocalic position. This difference might depend on whether the vowels are round [ɔ], [œ], [ʊ], and [ʏ] or nonround [ɑ], [e], [ɨ], [ɪ].

In the present study, it is aimed to elicit the place of articulation of fricative /h/ utilizing formant value changes, which were caused by formant transitions due to the production of the consonant /h/, in preceding and following vowels. In accordance with this purpose, the acoustic parameters used in this study were F1 related to the height feature of vowels, F2 associated to backness feature of vowels, and F3 relevant to rounding feature of vowels. Furthermore, F2_3 modeling, which is a new acoustic correlate in the field, was added to research as a parameter to determine if backness and rounding interaction would indicate significance.

Methodology

Speakers

Twenty-one native speakers between 18-35 years old (14 Female, mean age=26.00, SD=3.25, SE=0.87; 7 Male, mean age=28.71, SD=3.19, SE=1.20) were included into the production experiment. To avoid differences in dialect-based speech, all speakers were selected according to their regional background (generally from Ankara and İstanbul). Sample groups for speakers were chosen by the conditions of not having neurological, hearing, visual and/or language impairments. Experiment was approved by the Ankara University of the Ethical Board (Decision No: 233).

Experimental Design and Stimuli

The 64 (8x8) stimuli in the experimental design of the present study included trisyllable and disyllable words (40 pseudowords and 24 lexical words) that had all Turkish vowels [ɑ], [e], [ɨ], [ɪ], [ɔ], [œ], [ʊ], and [ʏ] in the position before and after intervocalic /h/ (see the stimuli list in Table 1).

Table 1. Stimuli list of preceding and following vowels used in the experiment

Preceding vowels in intervocalic position of /h/							
[ɑ]	[e]	[ɨ]	[ɪ]	[ɔ]	[œ]	[ʊ]	[ʏ]
C**ɑ**hɑC	C**e**haC	C**ɨ**haC	C**ɪ**haC	C**ɔ**haC	C**œ**haC	C**ʊ**haC	C**ʏ**haC
(all vowels x 8 different pairs of following vowel combinations)							
Following vowels in intervocalic position of /h/							
[ɑ]	[e]	[ɨ]	[ɪ]	[ɔ]	[œ]	[ʊ]	[ʏ]
Cɑh**ɑ**C	Cɑh**e**C	Cɑh**ɨ**C	Cɑh**ɪ**C	Cɑh**ɔ**C	Cɑh**œ**C	Cɑh**ʊ**C	Cɑh**ʏ**C
(all vowels x 8 different pairs of preceding vowel combinations)							

Abbreviations. C: Consonant.

Pseudowords were generated in a similar way of structure with lexical words by using phonological similarities. In the design of the study, 4032 combinations were obtained ((64 stimuli x 21 speakers) x 3 repetitions = 4032 combinations). Each stimulus with intervocalic /h/ were analyzed via Praat 6.0.42 (Boersma & Weenink, 2023). In a carrier sentence formulation such as [Adam zihin yazdı] > [The man mind write -PAST], each stimulus was read loudly by each speaker as natural as possible. There were also 128 filler structure combinations of /h/ located in the beginning and ending positions of the words such as: [Adam horoz yazdı] > [The man rooster write -PAST).

Procedure

The spoken data were recorded separately for each speaker in a soundproof booth at a phonetics laboratory using a dynamic stereo digital cardioid microphone at 44,100 Hz, 16-bit resolution, and saved in .wav format using Praat 6.0.42 software (Boersma & Weenink, 2023). All speakers were seated approximately 18 inches from the sound system. During the experiments, the researcher was seated in another glass-partied room. Before the main experiments, all speakers were informed on experiment instructions, informed consent form and laboratory rules. Each speaker performed a trial experiment including the same experimental conditions as to control their reading prosody. The stimuli were presented to speakers in a carrier sentence form in the center of a grey tablet screen. Speakers were asked to produce the sentence with three repetitions as natural as possible neither slow nor fast. They were not informed on their pronunciation errors. There were five recording sessions and four breaks after each session. Experiments lasted approximately forty-five minutes including breaks.

Data Analysis: Acoustic and Statistical Analyses

Acoustic data analysis was performed by using *FormantPro* (Xu & Gao, 2018) package under Praat (Boersma & Weenink, 2023). Each item was annotated with four acoustic parameters and prepared for statistical analyses in a .csv file format. Acoustic parameters were obtained via *FormantPro* as normalized mean F1, F2, F3, and F2_3 (Hz) frequencies of preceding and following vowels in intervocalic position of /h/. Before the annotations for script analysis, rawdata were prepared and renamed manually by separating the critical words from the carrier sentence formations (see Figure 1 for the Praat annotations). All pronunciation errors, unexpected pause, recording artefacts, and octave jumps were removed from the data during the first annotations. After the data prepared for the formant analysis, the script was run for interactive labelling and then all speakers were combined with ensembled files.

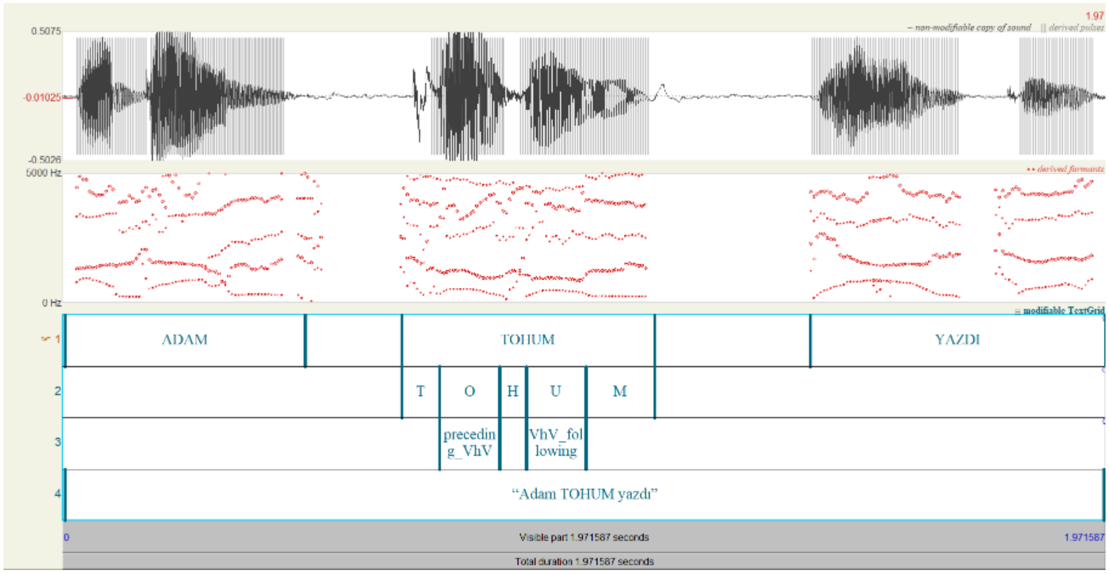

Figure 1. A sample for Praat annotations

Subsequently, statistical data analyses were conducted on R language (R Core Team, 2023) using linear mixed-effects model (LMMs) with *lme4* (Bates et al., 2015), *ggplot2* (Wickham, 2016), and *lmerTest* (Kuznetsova, Brockhoff & Christensen, 2017) packages. Fixed factors were ACOUSTICMEASURE (mean F1, F2, F3, F2_3), HEIGHT (low vs. high) and ROUNDNESS (round vs. non-round). Random factors were ITEM, GENDER and SPEAKER. Further analyses were performed by using pairwise analysis with *lsmeans* (Lenth, 2016) package for (ROUNDNESS:HEIGHT) interaction. As a result of model comparisons Akaike Information Criteria (AIC), the final statistical model with two-way interactions was formed as following: (ACOUSTICMEASURE ~ ROUNDNESS * HEIGHT + (1|SPEAKER) + (1|ITEM) + (1|GENDER).

Results

The statistical analysis for the normalized mean F1, F2, F3, and F2_3 frequencies were performed separately for the preceding and following vowels on the intervocalic position of Turkish /h/ to elicit place of articulation of the consonant building around effects on surrounding vowels. In the first section, we presented the LMMs findings for preceding vowels in terms of HEIGHT-ROUNDNESS interaction. Then, in the second section, we present the same interaction findings observed for the following vowels.

Preceding Vowels

Figure 2 shows the normalized mean data for the F1, F2, F3, and F2_3 frequencies of preceding vowels. As seen in the upper left corner of the figure (A), the mean F1 indicated high significancy for the HEIGHT-ROUNDNESS interaction ($p<0.005$). While the main effects for ROUNDNESS ($p=0.91$) did not show significance, HEIGHT ($p<0.001$) indicated a high level of significance. As seen in Table 2, although the pairwise analysis between all conditions showed significantly high results except for the high nonround-round vowels. Subsequently, the upper right corner of Figure 2 (B) did not show significance for the interaction between HEIGHT-ROUNDNESS for mean F2 ($p=0.69$). While the pairwise comparison tests for round-nonround vowels ($p<0.05$) elicited significance, findings for high-low vowels ($p=0.43$) did not show significance. Post-hoc comparison tests for only the low nonround-round vowels ($p<0.05$) revealed high performances.

The lower left corner of Figure 2 (C) shows the mean F3 values. Accordingly, HEIGHT-ROUNDNESS interaction did not indicate significantly important findings ($p=0.34$). Even though the main effects for the

ROUNDNESS ($p<0.001$) revealed significance, it was not significant for the HEIGHT ($p=0.78$). Similarly, the pairwise comparison tests of round-nonround ($p<0.001$) elicited significant, findings for high-low ($p=0.57$) did not elicit significancy. Post-hoc results for high nonround-round ($p<0.001$) and low nonround-round ($p<0.005$) vowel comparisons also showed significance. Lastly, as expected, the lower right corner of Figure 2 (D) for the mean F2_3 values did not show significance ($p=0.91$). Similar to previous findings, the main effects for ROUNDNESS ($p<0.005$) indicated significance, the results for HEIGHT ($p=0.82$) were not high. While the pairwise comparison tests for round-nonround ($p<0.001$) designated high level of significance, high-low ($p=0.67$) did not reveal significant findings. On the other hand, the comparisons were significant if only the round and nonround vowels were high ($p<0.001$) and low ($p<0.001$) (See Table 2).

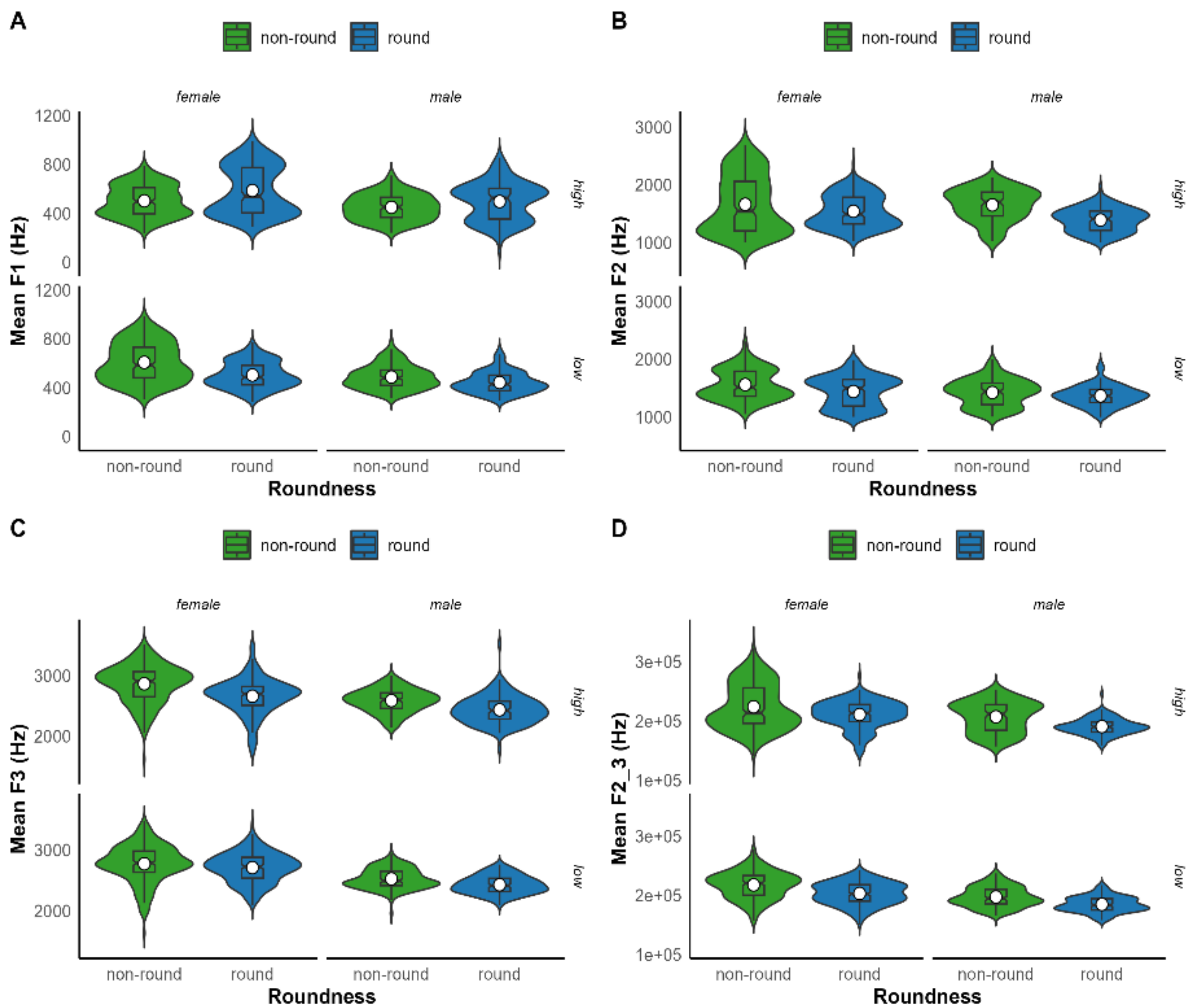

Figure 2. Normalized mean F1, F2, F3 and F2_3 for the preceding vowels

Table 2. Fixed-effects and pairwise comparisons for the preceding vowels

Comparisons	*Fixed effects*			
Mean F1				
	B	*SE*	*t*	*P*
(Intercept)	*438.25*	*29.73*	*14.73*	*<0.005***
Roundness	-2.56	23.26	-0.11	0.91
Height	181.65	23.26	7.80	**<0.001*** **
Roundness×Height	-107.82	32.89	-3.27	**<0.005** **
Round×Nonround	56.47	16.44	3.43	**<0.005** **
High×Low	-127.73	16.44	-7.76	**<0.001*** **
Nonround:High×Round:High	2.56	23.26	0.11	0.91
Nonround:High×Nonround:Low	-181.65	23.26	-7.80	**<0.001*** **
Round:High×Round:Low	-73.82	23.26	-3.17	**<0.005** **
Nonround:Low×Round:Low	110.38	23.26	4.74	**<0.001*** **
Mean F2				
(Intercept)	*1654.99*	*79.19*	*20.89*	*<0.001****
Roundness	-123.81	83.48	-1.48	0.14
Height	-18.15	83.48	-0.21	0.82
Roundness×Height	-57.38	118.06	-0.48	0.62
Round×Nonround	152.50	59.03	2.58	**<0.05***
High×Low	46.84	59.03	0.79	0.43
Nonround:High×Round:High	123.81	83.48	1.48	0.14
Nonround:High×Nonround:Low	18.15	83.48	0.21	0.82
Round:High×Round:Low	75.53	83.48	0.90	0.36
Nonround:Low×Round:Low	181.20	83.48	2.17	**<0.05***
Mean F3				
(Intercept)	*438.25*	*29.73*	*14.73*	*<0.005***
Roundness	-139.94	29.50	-4.74	**<0.001*** **
Height	-8.20	29.50	-0.27	0.78
Roundness×Height	39.96	41.72	0.95	0.34
Round×Non-round	119.95	20.86	5.74	**<0.001*** **
High×Low	-11.77	20.86	-0.56	0.57
Nonround:High×Round:High	139.94	29.50	4.74	**<0.001*** **
Nonround:High×Nonround:Low	8.20	29.50	0.27	0.78
Round:High×Round:Low	-31.76	29.50	-1.07	0.28
Non-round:Low×Round:Low	99.97	29.50	3.38	**<0.005** **
Mean F2_3				
(Intercept)	*219.10*	*94.40*	*23.24*	*<0.005***
Roundness	-148.98	53.15	-2.80	**<0.005** **
Height	-12.06	53.15	-0.22	0.82
Roundness×Height	-7.66	75.17	-0.10	0.91
Round×Nonround	152.82	37.58	4.06	**<0.001*** **
High×Low	15.89	37.58	0.42	0.67
Nonround:High×Round:High	148.98	53.15	2.80	**<0.005** **
Nonround:High×Nonround:Low	12.06	53.15	0.22	0.82
Round:High×Round:Low	-13.69	53.15	0.37	0.71
Nonround:Low×Round:Low	156.65	53.15	2.94	**<0.005** **

*Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Following Vowels

Figure 3 represents the normalized mean data for all formant frequencies of following vowels. In the upper left corner of Figure 3 (A), the mean F1 indicated high significancy for the HEIGHT-ROUNDNESS interaction (p<0.005). Even though the main effects for the ROUNDNESS (p<0.06) were on the significance border, the HEIGHT ($p<0.05$) indicated significancy. As seen in Table 3, post-hoc analysis was only significant for nonround high-low ($p<0.05$) and low nonround-round ($p<0.05$) vowels. Next, the upper right corner of the Figure 3 (B) showed high performance for mean F2 values for the main effects of HEIGHT ($p<0.05$) and ROUNDNESS ($p<0.05$). However, the interaction between HEIGHT-ROUNDNESS ($p=0.47$) was not significant. Pairwise comparison tests were significantly high for only the round-nonround ($p<0.05$), high-low ($p<0.05$), and high round-nonround ($p<0.05$) vowel combinations.

On the other hand, the lower left corner of the Figure 3 (C) displaying the mean F3 elicited high interaction ($p<0.05$) and main effects both for the ROUNDNESS ($p<0.005$) and HEIGHT ($p<0.001$) conditions. Results were also significant for the pairwise comparisons between round-nonround ($p<0.001$), high round-nonround ($p<0.001$), nonround high-low ($p<0.005$), and low round-nonround ($p<0.05$). For the lower right corner of Figure 3 (D) on the mean F2_3 values did not indicate high performances. As a result of the F2 and F3 combinations, while main effect of ROUNDNESS ($p<0.05$) was significant, the findings were not significant for the main effect of HEIGHT ($p=0.16$) and the interaction of both ($p=0.92$). Post-hoc comparisons were significant only for the round-nonround ($p<0.001$), high round-nonround ($p<0.05$), low round-nonround ($p<0.05$) vowel combinations (see Table 3).

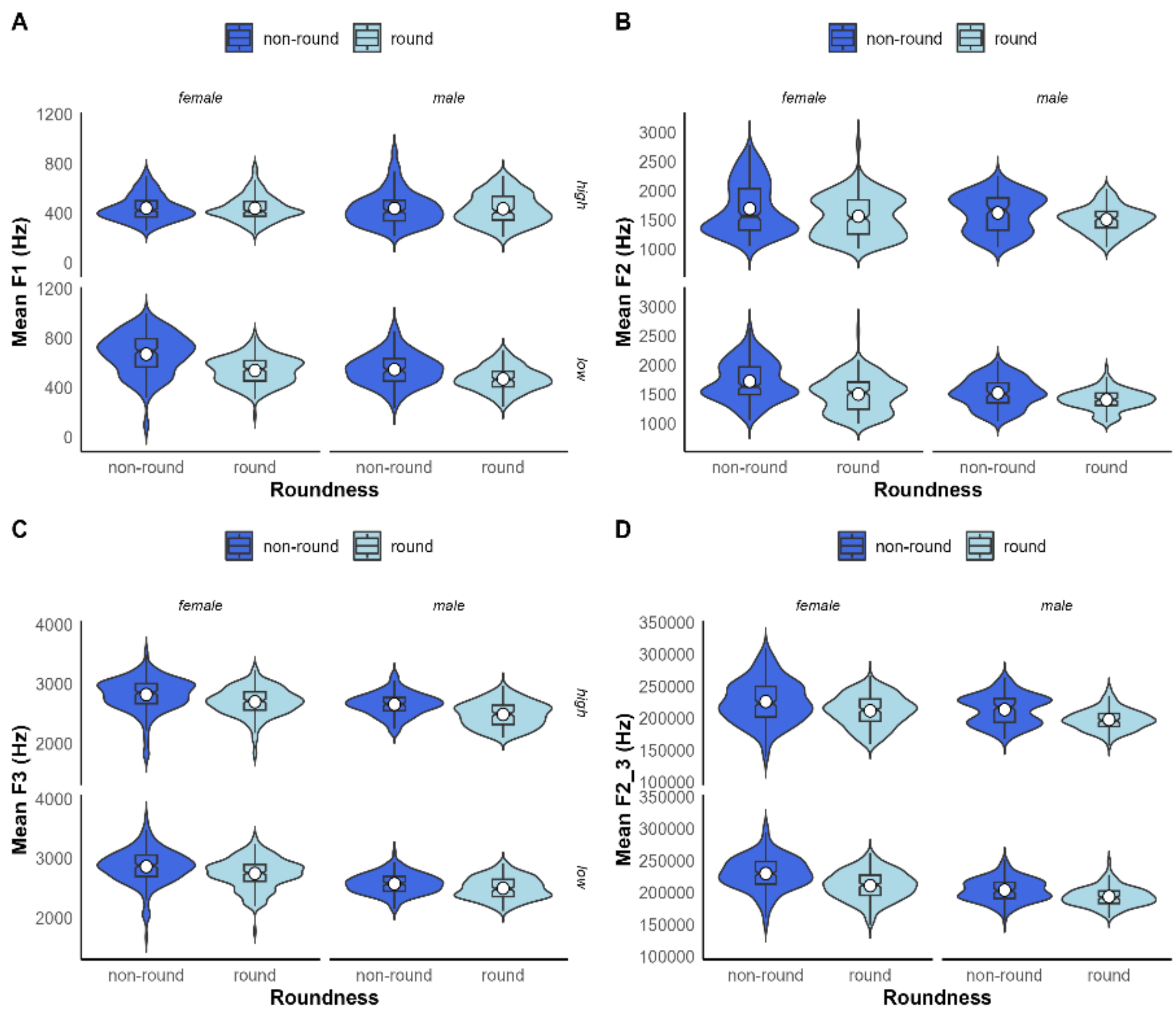

Figure 3. Normalized mean F1, F2, F3 and F2_3 values for the following vowels

Table 3. Fixed-effects and pairwise comparisons for the following vowels

Comparisons	*Fixed effects*			
Mean F1				
	B	*SE*	*t*	*P*
(Intercept)	*473.82*	*48.46*	*9.77*	*<0.005***
Roundness	70.89	37.75	1.87	0.06
Height	79.91	37.75	2.11	**<0.05***
Roundness×Height	-152.55	53.39	-2.85	**<0.005****
Round×Nonround	5.37	16.44	0.20	0.84
High×Low	-3.63	16.44	-0.13	0.89
Nonround:High×Round:High	-70.89	23.26	-1.87	0.06
Nonround:High×Nonround:Low	-79.91	23.26	-2.11	**<0.05***
Round:High×Round:Low	72.63	23.26	1.92	0.05
Nonround:Low×Round:Low	81.65	23.26	2.16	**<0.05***
Mean F2				
(Intercept)	*1648.19*	*71.44*	*23.07*	*<0.001****
Roundness	-173.84	77.35	-2.24	**<0.05***
Height	-150.63	77.35	-1.94	0.05
Roundness×Height	77.78	109.39	0.71	0.47
Round×Nonround	134.95	54.69	2.46	**<0.05***
High×Low	111.74	54.69	2.04	**<0.05***
Nonround:High×Round:High	173.84	77.34	2.24	**<0.05***
Nonround:High×Nonround:Low	150.63	77.34	1.94	0.05
Round:High×Round:Low	72.85	77.34	0.94	0.34
Nonround:Low×Round:Low	96.06	77.34	1.24	0.21
Mean F3				
(Intercept)	*273.20*	*130.46*	*20.94*	*<0.05**
Roundness	-184.18	29.52	-6.23	**<0.001*****
Height	-81.72	29.51	-2.76	**<0.005****
Roundness×Height	107.51	41.74	2.57	**<0.05***
Round×Non-round	130.43	20.87	6.24	**<0.001*****
High×Low	27.96	20.87	1.34	0.18
Nonround:High×Round:High	184.18	29.52	6.23	**<0.001*****
Nonround:High×Nonround:Low	81.72	29.51	2.76	**<0.005****
Round:High×Round:Low	-25.78	29.52	-0.87	0.38
Non-round:Low×Round:Low	76.67	29.51	2.59	**<0.05***
Mean F2_3				
(Intercept)	*215297.70*	*10198.82*	*21.11*	*<0.05**
Roundness	-144.18	54.44	-2.64	**<0.05***
Height	-7.65	54.44	-1.40	0.16
Roundness×Height	7.16	76.99	0.09	0.92
Round×Nonround	140.60	38.49	3.65	**<0.001*****
High×Low	72.94	38.49	1.89	0.06
Nonround:High×Round:High	144.18	54.44	2.64	**<0.05***
Nonround:High×Nonround:Low	7.65	54.44	1.40	0.16
Round:High×Round:Low	6.93	54.44	1.27	0.20
Nonround:Low×Round:Low	137.01	54.44	2.51	**<0.05***

*Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Discussion and Conclusion

The present study aimed to investigate the acoustic characteristic changes of the surrounding vowels resulted from articulation of consonant /h/ in intervocalic position in Standard Turkish to get insight into place of articulation of consonant /h/. To this end, we conducted a production experiment examining the formant transitions and comparisons of F1, F2, F3, and F2_3 formant frequencies between preceding and following vowels. Accordingly, comparison of normalized values of F1, F2, F3, and F2_3 formant frequencies considering preceding and following position might define the place of articulation of consonant /h/. As we expected, our LMMs analysis showed significantly important results for the acoustic characteristics of normalized mean F1 and F2 formant frequencies for the vowel height and roundness which are the results of production of /h/.

Findings from the interaction analyses between surrounding vowel height and roundness might indicate that the normalized mean F1 formant frequency decreased for preceding vowels, however; the normalized mean F1 frequency increased when the following vowels were high and round. This finding supports Pickett's (1999) discussion on tongue position differences for F1 and F2. Accordingly, Pickett claims that when the tongue rises, F1 formant frequency decreases, and when the tongue lowers, F1 increases. The increase in F1 frequency for the following vowels suggests that the production of the consonant /h/ might affect only the following vowels, leading to higher F1 frequencies (Pickett, 1999; Kent & Read, 2002; Zsiga, 2013). A well-known study by Johnson (2003) highlighted that, due to the presence of multiple nodes for the F3 formant frequency extending from the velum to the alveolar ridge, any constriction in the posterior region of the vocal tract may lead to a decrease in the F3 value during production. Zsiga (2013) refers that F2 is related to the horizontal position of the tongue in oral cavity. Accordingly, investigating F2 and F3 values might give insight into articulation of /h/. In the interaction between vowel height and roundness, low mean F2 has been observed when high and low vowels in the preceding position are rounded while high F2 are visible for vowels in the following position due to the effect of glottal articulation in intervocalic position. Our findings for the interaction between height and roundness showed that the mean F3 of both preceding and following vowels decreased due to the effect of lip rounding. No change in F3 value indicated that the production of consonant /h/ might not influence the vocal tract length or lip rounding owing to the open oral tract during the articulation of vowels and the /h/ consonant. Lastly, our findings from F2_3 calculation (Xu & Gao, 2013) showed that the mean normalized F2_3 values for the surrounding vowels decreased as an effect of lip rounding. F2_3 particularly reflected the acoustic changes in F3 frequency and decreased the impact of lip rounding.

Building upon Ertan's (2013) findings, which discuss /h/ acoustically aligns with surrounding vowels in syllable-initial and syllable-final positions, our study extents the investigation to the intervocalic positions of surrounding vowels across /h/ in Turkish. From this motivation, our results further demonstrate that the glottal articulation of /h/ in Turkish shows significant formant frequency shifts in response to adjacent vowels' acoustic characteristics. This supports the claim that /h/ retains its distinctive glottal articulation while acting as a transitional element acoustically impacted by its phonological surroundings in Turkish. From all these perspectives, we considered that the glottal articulation of the consonant /h/ in Turkish might represent a higher F1 frequency at the beginning of the following vowels. Our findings also showed that significantly high results at F1 and F2 frequencies resulted from the glottal articulation challenge with the Skandera and Burleigh (2005)'s hypothesis that consonant /h/ is a cavity fricative. Therefore, the higher values at low frequencies for following vowels may result from the production of intervocalic /h/ in vocal tract. Previous works in Turkish (Kılıç, 2012; Ertan, 2013) discussed the acoustic characteristics of /h/ and the adjacent vowels except their voicing features with limited sample groups. In contrast to these studies, our findings with LMMs analyses from a large sample group and stimuli suggested that consonant /h/ in Turkish might carry the acoustic characteristics of glottal consonant affecting the vowel height and lip rounding of the following vowels.

To conclude, our results from the production experiment with a large sample group and stimuli for the surrounding vowels in intervocalic /h/ indicated a strong interaction between F1 and F2 formant frequencies for height and roundness interaction, which arises from articulation of /h/. Our findings did not reveal significance in F3 and F2_3 formant frequencies for height and roundness interaction, compared between preceding and following vowels. As expected, the extent of vowel height and rounding features for surrounding vowels were more significant for the following vowels compared to preceding vowels in intervocalic positions. Using F2_3 modeling as an acoustic parameter for surrounding vowels attributes specificity to study and even though our primary findings for surrounding vowels for intervocalic /h/

supported the previous works, further acoustic based studies are needed to investigate the different subcomponents of /h/ in Turkish.

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