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Acoustic Analysis of Persian Plosives in Hearing-impaired and Normal-Hearing Children: A Study of VOT and F0 of Onset

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Abstract

The present study explored the effects of voicing and place of articulation on voice onset time (VOT) and fundamental frequency (F0) of onset of Persian oral plosives uttered by normal hearing (NH) and hearing-impaired (HI) children. Twenty-one NH children and twenty-one HI children matched for age and gender took part in this study. The participants were asked to repeat 36 CV words including all eight Persian plosives (/p/, /t/, /k/, /c/, /b/, /d/, /g/, /ɟ/) in combination with the vowel /æ/. All syllables were recorded in a nearly sound-proof room using PRAAT Software. Independent samples t-test was used to compare the groups across gender. The results revealed: (a) HI children had higher VOT and F0 of onset values in nearly all aspects except for VOT and F0 onset of voiced plosives and F0 onset of alveolar and velar plosives; (b) both groups of girls had higher VOT values than boys did; (c) VOT is affected by the place of articulation and F0 is related to voiced-voiceless classification of plosives. Overall, NH children were able to distinguish and produce sounds more correctly, implying that HI children need further training. The study has implications for speech therapists, clinical linguists, and application designers to focus on speech sounds which are challenging for HI children to produce.

Keywords: voice onset time (VOT), fundamental frequency (F0), hearing-impaired children, normal children

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1. Introduction

Voice onset time (VOT) is the most important acoustic cue served to distinguish initial oral plosives (Awoonor Aziaku, 2021; Karia, 2023). According to Karia (2023), VOT is the time between the release of the burst and the onset of vibration of vocal folds. VOT can be positive, negative or zero (McCrea & Morris, 2007; Kaur, 2015) depending on the voicing properties of plosives. If vocal folds vibrate after the release of the consonant, VOT is positive and the sound is said to have a voicing lag; if, on the other hand, vocal folds vibrate prior to consonant release, the resultant sound has a voicing lead and its VOT value is negative; and if the vocal folds vibrate simultaneously with the consonant release, the VOT value is zero (McCrea & Morris, 2007; Kaur, 2015). For example, English voiceless plosives (/p/, /t/, /k/) have long-positive VOT (30-100 ms) and thus have voicing lag, while the voiced plosives have either short-positive VOT (0-25) or negative VOT (-100-0) which is called voicing lead (Karia, 2023).

1.1. Phonology of Persian Plosive Consonants

Standard Persian language has 6 vowels and 23 consonants, 8 of which are plosives; two bilabial plosives /p,b/, two dental ones /t,d/, two palatal ones /k,g/, one uvular plosive /G/, and one glottal one /ʔ/ (Samare, 2008). Depending on the place of articulation, /k/ and /g/ have two allophones each. If they precede back vowels, they become velar /k/ and /g/, but if they come before front vowels, they become palatal /c/ and /ɟ/. /G/ is mainly a voiced plosive found in Persian language, but it is voiceless /q/ in some dialects like Kermani dialect which is spoken in Kerman. Since this article was conducted in Kerman, we took both allophones into account in this article. Therefore, the current study focuses closely on analyzing Persian oral plosives in hearing-impaired children and normal hearing children concerning VOT and F0 of onset.

2. Literature Review

2.1. Hearing Impairment

Hearing impairment, as the name suggests, is a complication which causes people to be deprived of hearing whole or part of sentences being uttered. It is the most frequent sensory deficit in human populations, affecting more than 250 million people in the world (WHO, 2023). According to Finitzo and Crumley (1999), it is considered to be the most prevalent congenital abnormality in new-borns and is more than twice as prevalent as other conditions that are screened for at birth, such as sickle cell disease, hypothyroidism, phynilketonuria, and galactosaemia. It is caused by many different factors, including aging, exposure to noise, illness, chemicals and physical trauma, genetics or any combination of these (Zadeh & Selesnick, 2001).

One of the most devastating effects of hearing loss or impairment is that speech is not developed normally and completely, which leads to poor communication (Cole & Flexer, 2019). Since this disease is not diagnosed early or its treatment is postponed after language development years, most HI children have difficulty producing speech sounds and must be taught how to pronounce sounds and words.

2.2. Voice onset Time (VOT) and Its Correlates

According to Karia (2023), VOT is the time between the release of the burst and the onset of vibration of vocal folds. VOT can be positive, negative or zero (McCrea & Morris, 2007; Kaur, 2015) depending on the voicing properties of plosives. Previous research has shown that VOT of English stops changes according to the gender of speakers (e.g., Koenig, 2000). Some researchers have pointed out women produce longer VOTs than men (e.g., Robb et al., 2005; Ryalls et al., 1997; Wadnerker et al., 2006). In their study on British girls and boys, Whiteside et al. (2004) showed that girls had longer VOT values than boys. On the other hand, Yu et al. (2016) showed longer VOTs in males than in females. Morris et al. (2008) showed no difference between males and females in terms of VOT values. These differences can be mainly due to physiological properties found in vocal apparatus of both genders. Concerning laryngeal anatomy, for example, supra-glottal cavity is mainly larger in men than in women and vocal tract volume is smaller in women (Simpson & Weirich, 2020; Trollinger, 2003).

Another factor which affects VOT is the place of articulation. As for place of articulation, three main principles have been proposed by researchers: (1) The further back the closure, the longer the VOT (Cho & Ladefoged, 1999). For example, velars have higher VOT values than dentals and dentals have higher values than bilabials. It can be explained according to the aerodynamic law. Cho and Ladefoged (1999) stated that in order for vocal folds to vibrate, there must be a difference in air pressure beneath and above them. Since the volume behind velars is less than that behind the alveolar and bilabials, the air pressure is higher in velars and thus their VOT is higher. (2) If the contact area between two articulators is more extended, the created VOT is higher (Cho & Ladefoged, 1999). For instance, velars which are produced by body of the tongue touching soft palate have higher VOTs than alveolar plosives in which tip of the tongue and alveolar ridge are involved. (3) Fast movement of articulators results in shorter VOTs (Hardcastle, 1973). Hardcastle (1973) claimed that tip of the tongue and lips move faster than other parts of the tongue; therefore, sounds created by body of the tongue have longer VOTs than those produced by tip of the tongue.

2.3. Fundamental Frequency (F0) of Onset

Fundamental frequency (F0) of onset is a feature which distinguishes voiced from voiceless plosives (Trolinger, 2003). Some researchers have pointed out F0 of onset is related to the phonological features of initial-stop voicing, thus varying according to laryngeal timing; that is, F0 of onset following voiceless stops is higher than that following voiced stops (Hombert, 1978; Whalen, 1990). According to Lea (1973), F0 decreases after voicing onset in voiceless aspirated stops, while it increases after voiced stops. He has also mentioned that this rise-fall trend in F0 is a good indicator to distinguish between voiced and voiceless stops. Hombert (1978) and Ohala (1978) believed that this is an intrinsic pattern which is not controlled by the speaker but rather by physiological and aerodynamic properties. Hombert et al. (1979) examined aerodynamic theory and showed that changes in F0 of onset were mainly related to vertical tension in the larynx. In their study on Thai et al. (1978) showed that changes in F0 of onset were shorter in tonal languages than in non-tonal languages. In addition, some other researchers showed that non-tonal languages like English, French, and Dutch had higher changes in F0 of onset (100 ms or more) (Hombert, 1978; Whalen, 1990). Another reason attributed to onset F0 changes is physiological mechanisms found in vocal tract of speakers. Lowell et al. (2012) have posited that positions of the larynx and hyoid bone are higher in voiceless stops than in voiced ones. As Ohala (1978) pointed out, lowered larynx causes lowered F0.

The aim of the present research was to analyse Persian oral plosives in hearing-impaired children and normal hearing children concerning VOT and F0 of onset. To do so, three main variables of voicing of plosive consonants, gender, and hearing status were taken into account and the following research questions were raised:

1- Is the amount of VOT of initial oral plosives in the speech production of hearing-impaired children different from normal hearings, concerning gender, voicing, manner of articulation and place of articulation of plosives?
2- Is the amount of F0 of onset of initial oral plosives in the speech production of hearing-impaired children different from normal hearings, concerning gender, voicing, manner of articulation and place of articulation?

3. Methodology

3.1. Participants

Twenty-one hearing-impaired school-aged children (15 boys and 6 girls, aged 9-12) and twenty-one normal hearing school-aged children (15 boys and 6 girls, aged 9-12) participated in this study. All normal children had similar situations concerning social class, school, and living conditions; all hearing-impaired children had also similar situations regarding hearing status, use of hearing aid (average 5 years), hearing residues (profound hearing-impaired children), and duration of using hearing aids in a way that all of them were profoundly hearing-impaired children who used hearing aids for more than four years. Since parents of only 21 hearing-impaired children accepted to cooperate with the researchers, normal hearing counterparts were selected based on age and sex of the HI ones. All HI children had no other disease or disability which deprived them of going to school and of learning Persian language. All 42 subjects repeated seven CV syllables twice. Both repetitions were recorded using PRAAT and the clearest utterances were selected and analysed using SPSS (version 19) software.

3.2. Equipment

In order to record sounds uttered by children, a headphone (A4TECH HS-50) which was positioned approximately 25-30 cm from the subjects' mouths and a notebook computer (Asus) were used. Using PRAAT Software (version 5.3.17), the high-quality CV syllable was selected and extracted. After all data were collected and extracted, VOT and F0 of onset of each syllable were measured.

3.3. Procedure

In order to have the best sound waves, all participants attended a nearly sound-proof room and their utterances including seven Persian plosives /p, b, t, d, k, g, c, ɟ, G/ plus the front open vowel /æ/ (/pæ/ /bæ/ /tæ/ /dæ/ /kæ/ /gæ/ /Gæ/) were recorded twice. Since HI children had been selected from different grades of elementary school, their literacy knowledge was different and thus their reading speed and proficiency was different. Therefore, they were asked not to read the CV syllables but rather to repeat them after the researcher. After all utterances were recorded, PRAAT Software was used to measure VOT and F0 of onset of all recorded utterances. Moreover, four places of articulation including bilabial, alveolar, palatal and uvular were also analysed by PRAAT Software. In order to measure VOT of the utterances, the time difference between the burst and the onset of voicing must be measured using Keating et al. (1981) measurement method. As for F0 of onset, four pitch periods from the beginning of vibration were measured. After that, SPSS (version 19) was used to analyse the collected data. Tests of normality were done, suggesting that all the data were normally distributed. For this reason, Independent Samples T-Test was selected and used to analyse the extracted data.

4. Results

4.1. VOT of Plosives in Terms of Voicing

As shown in Table 1, mean VOT values of voiced plosives was lower in normal boys than in HI peers ($p>0.05$), and it showed that normal boys had higher pre-voicing values than their HI counterparts. Concerning voiceless plosives, HI boys had higher mean, range, and standard deviation ($p>0.05$). It showed that since HI children produced speech sound somehow artificially, they used more energy and force to push the sounds outwards, thus more aspiration was produced.

Regarding girls, HI girls had positive VOT for voiced plosives, while normal girls had negative VOT values ($p<0.05$). It revealed that HI girls, like HI boys, had more tendencies to produce voiceless-like sounds. This is completely obvious in voiceless sounds; HI girls had higher VOT values in voiceless plosives ($p<0.05$) which was similar to the findings related to HI boys.

Table 1 presents normal hearing girls had higher VOT values than normal boys regarding voiced plosives ($p>0.05$) and had a bit higher VOTs in voiceless plosives ($p>0.05$). Besides, HI girls had positive VOT values for voiced plosives, while HI boys had negative values and the difference was significant ($p<0.05$). This can be due to girls' difficulties in controlling their vocal cords; that is, they couldn't vibrate their vocal cords and thus the sounds they produce had less vibration. Concerning voiceless plosives, girls had higher values than boys ($p>0.05$). It showed that HI girls had less control on their vocal cords than HI boys and thus produced words with less vibration. Consequently, their uttered sounds (whether voiced or voiceless) seemed to be voiceless rather than voiced.

Generally, mean VOT of voiced plosives was more negative in normal children than in HI ones ($p>0.05$). For voiceless plosives, HI children had longer VOT values, and the difference was significant between these two groups ($p<0.05$). In this respect, there were no significant differences across genders.

Table 1

Central and Dispersion Indexes of VOT Values in HI and NH Children in Terms of Voicing

Hearing Status	Sex	N	Voicing of Plosive	Mean	Min.	Max.	Range	SD
NH	Boy	15	Voiced	-34.3	-88.3	10.3	98.7	31.2
			Voiceless	40	23.3	54.0	30.8	9.3
	Girl	6	Voiced	-11.2	-45.0	13.3	58.3	21.7
			Voiceless	40.4	31.8	54.3	22.5	9.3
	Total	21	Voiced	-27.6	-88.3	13.3	101.7	30.2
			Voiceless	40.1	23.3	54.3	31.0	9.1
HI	Boy	15	Voiced	-25.5	-91.3	39.3	130.7	41.2
			Voiceless	51.8	22.8	91.3	68.5	22.0
	Girl	6	Voiced	15.3	-1.0	37.0	38.0	14.0
			Voiceless	66.4	55.5	82.5	27.0	9.1
	Total	21	Voiced	-13.8	-91.3	39.3	130.7	39.9
			Voiceless	56.0	22.8	91.3	68.5	20.2

Note: NH=normal hearing; HI=hearing impaired

4.2. VOT of Plosives in Terms of Place of Articulation

As presented in Table 2, mean VOT values was much higher in HI boys than in normal peers in all four places of articulation including bilabial, alveolar, palatal, and uvular plosives ($p<0.05$). In both groups, bilabial plosives had the least VOTs; alveolars had less VOTs than palatals (alveolar and palatal plosives had the same VOT value in HI boys); and palatals had less values than uvulars.

Although HI girls had higher VOT values than their normal peers in all four places of articulation, the same effect of place of articulation on VOT was not observed here. In both groups, alveolar plosives had the least VOT values; uvulars, palatals, and bialabials had the highest VOTs respectively.

Table 2 indicates normal girls had higher VOT values than normal boys regarding all four places of articulation but it was not significant ($p>0.05$). In boys, bilabials had the least VOT values, alveolars had lower VOTs than palatals, and palatals have lower VOTs than uvulars. Girls followed the same trend except that alveolars had less VOT values than bialabials. Physiological properties were the most common factors causing higher VOTs in girls. As shown in Table 2, HI girls had much higher VOT values in all places of articulation than HI boys ($p>0.05$), but it was not significant. The trend was exactly the same for the normal groups except that HI boys had the same values for alveolars and palatals.

Generally, mean VOT of HI children was much higher than that of normal ones ($p>0.05$). In normal children, bilabial plosives had the least VOT, alveolars had less VOTs than palatals, and palatals had less values than uvulars. However, in HI children, alveolar plosives had the least VOT values, uvulars, palatals, and bialabials had the highest VOTs respectively.

Table 2

Central and Dispersion Indexes of VOT Values in HI and NH Children in Terms of Place of Articulation

Hearing status	Gender	N	Place of articulation	Mean	Min.	Max.	Range	SD
NH	Boy	15	Bilabial	0.8	-28.0	25.0	53.0	17.4
			Alveolar	6.7	-32.0	34.5	66.5	21.3
			Palatal	13.6	-25.5	49.0	74.5	22.0
			Uvular	15.1	-45.0	84.0	129.0	39.0
	Girl	6	Bilabial	15.8	-12.5	31.0	43.5	17.3
			Alveolar	13.8	-6.0	30.0	36.0	15.5
			Palatal	21.0	-5.5	58.0	63.5	25.7
			Uvular	27.0	-25.0	75.0	100.0	32.9
	Total	21	Bilabial	5.0	-28.0	31.0	59.0	18.3
			Alveolar	8.7	-32.0	34.5	66.5	19.7
			Palatal	15.6	-25.5	58.0	83.5	22.7
			Uvular	18.5	-45.0	84.0	129.0	36.9
HI	Boy	15	Bilabial	11.6	-38.0	71.5	109.5	33.9
			Alveolar	17.3	-11.0	70.0	81.0	25.2
			Palatal	17.3	-17.0	61.0	78.0	22.7
			Uvular	38.3	-25.0	126.0	151.0	44.9
	Girl	6	Bilabial	40.8	18.0	69.5	51.5	19.0
			Alveolar	23.9	8.5	45.0	36.5	12.6
			Palatal	43.9	25.0	70.5	45.5	15.1
			Uvular	94.2	56.0	134.0	78.0	35.6
	Total	21	Bilabial	19.9	-38.0	71.5	109.5	32.8
			Alveolar	19.1	-11.0	70.0	81.0	22.1
			Palatal	24.9	-17.0	70.5	87.5	23.8
			Uvular	54.2	-25.0	134.0	159.0	48.9

Note: NH=normal hearing; HI=hearing impaired

4.3. F0 of Onset of Plosives in Terms of Voicing

As indicated in Table 3, mean F0 of onset values of voiced plosives was higher in normal boys than in HI peers ($p>0.05$). F0 of onset of voiceless plosives was a bit higher in HI boys than in normal boys ($p>0.05$). It was higher in HI girls than in normal ones both in voiced ($p>0.05$) and voiceless ($p<0.05$) plosives.

Normal girls had slightly higher F0 of onset in voiced stops than normal boys ($p>0.05$), while they had a bit lower F0 of onset in voiceless stops than boys ($p>0.05$). HI girls had higher F0 of onset than boys in both voiced and voiceless ones ($p>0.05$). Concerning voiced plosives, normal children had higher F0 of onset than HI ones, while they had lower F0 of onset for voiceless stops ($p>0.05$) and it was not significant.

Table 3

Central and Dispersion Indexes of F0 of Onset Values in HI and NH Children in Terms of Voicing

Hearing status	Sex	N	Voicing of plosive	Mean	Min.	Max.	Range	SD
NH	Boy	15	Voiced	271.0	199.8	332.5	132.7	29.2
			Voiceless	280.2	220.6	318.5	97.9	27.6
	Girl	6	Voiced	277.7	265.7	289.2	23.5	9.4
			Voiceless	279.1	268.9	288.8	19.9	7.3
	Total	21	Voiced	272.9	199.8	332.5	132.7	25.0
			Voiceless	279.9	220.6	318.5	97.9	23.4
HI	Boy	15	Voiced	256.5	182.8	429.0	246.2	57.2
			Voiceless	284.2	242.3	417.0	174.8	41.1
	Girl	6	Voiced	296.7	243.6	367.5	123.9	40.6
			Voiceless	317.0	280.0	362.7	82.8	37.5
	Total	21	Voiced	267.9	182.8	429.0	246.2	55.2
			Voiceless	293.6	242.3	417.0	174.8	42.0

Note: NH=normal hearing; HI=hearing impaired

4.4. F0 of Onset of Plosives in Terms of Place of Articulation

Bilabial and alveolar plosives had higher F0 of onset in normal boys than in HI boys ($p>0.05$), while palatal and uvular stops had higher F0 of onset in HI boys ($p>0.05$). Comparing HI girls with normal girls, HI girls had significantly higher F0 of onset in bilabial ($p<0.05$), alveolar ($p>0.05$), and uvular ($p<0.05$) plosives, but had lower F0 of onset in palatal ($p>0.05$) plosives; the difference was significant in the first three ones but not significant in the last one.

Normal children had lower F0 of onset for bilabial stops ($p<0.05$), higher F0 of onset for alveolars ($p<0.05$), higher F0 of onset for palatal stops ($p>0.05$), and lower F0 of onset in uvular plosives ($p>0.05$), compared to HI children. Therefore, a significant difference was observed between both groups concerning front places of articulation (bilabial and alveolar plosives), but no significant difference was observed in back places of articulations (palatal and uvular plosives).

Table 4

Central and Dispersion Indexes of F0 of Onset Values in HI and NH Children in Terms of Place of Articulation

Hearing status	Sex	N	Place of articulation	Mean	Min.	Max.	Range	SD
NH	Boy	15	Bilabial	281.8	211.0	315.4	104.4	27.1
			Alveolar	277.9	206.1	320.1	114.0	32.5
			Palatal	276.8	218.2	331.0	112.8	29.2
			Uvular	260.9	0.0	324.9	324.9	78.4
	Girl	6	Bilabial	273.3	252.0	292.6	40.6	17.4
			Alveolar	285.0	269.9	294.2	24.4	10.0
			Palatal	282.0	274.4	285.6	11.2	3.9
			Uvular	269.0	260.4	273.2	12.9	4.8
	Total	21	Bilabial	279.3	211.0	315.4	104.4	24.6
			Alveolar	279.9	206.1	320.1	114.0	27.8
			Palatal	278.2	218.2	331.0	112.8	24.6
			Uvular	263.2	.0	324.9	324.9	65.7
HI	Boy	15	Bilabial	276.0	239.9	443.3	203.4	47.9
			Alveolar	262.3	168.2	410.5	242.3	54.4
			Palatal	271.1	135.6	435.8	300.2	61.6
			Uvular	287.4	245.1	376.0	130.9	32.4
	Girl	6	Bilabial	341.2	303.9	400.5	96.6	46.6
			Alveolar	312.1	285.3	347.3	61.9	29.0
			Palatal	265.6	146.0	331.9	185.8	63.9
			Uvular	320.3	277.8	394.3	116.6	57.9
	Total	21	Bilabial	294.6	239.9	443.3	203.4	55.3
			Alveolar	276.5	168.2	410.5	242.3	53.0
			Palatal	269.5	135.6	435.8	300.2	60.7
			Uvular	296.8	245.1	394.3	149.2	42.4

Note: NH=normal hearing; HI=hearing impaired

5. Discussion and Conclusions

The present study aimed to analyse the initial oral plosives produced by HI children and their normal counterparts. For this purpose, two main variables of VOT and F0 of onset were taken into consideration. VOT is known to be the most reliable acoustic cue for the distinction between voiced and voiceless stops and this temporal characteristic of stop consonant reflects the complex timing of supralaryngeal-laryngeal coordination. F0 of onset is a term used in acoustic phonetics, referring to the lowest frequency component in a complex sound wave (Papakyritsis, 2021).

The acoustic analysis of VOT in HI and NH children revealed that the former group had higher VOT values in almost all aspects and all places of articulation except for VOT values related to voiced plosives. This is mainly due to the way children learn to speak. Since NH children learn to speak normally, they need no artificial control on their vocal cords and can produce some of them as fully-voiced sounds at the beginning of the words. However, HI ones artificially control and manipulate their vocal folds which results in abnormal vibration which is less than the vibration in the contrast children.

Mean VOT values was much higher in HI boys than in normal peers in all four places of articulation including bilabial, alveolar, palatal, and uvular plosives. In both groups, bilabial plosives had the least VOTs; alveolars had less VOTs than palatals (alveolar and palatal plosives had the same VOT value in HI boys); and palatals had less values than uvulars. These findings are consistent with the findings of many researchers about the effects of place of articulation on VOT values (Cho & Ladefoged, 1999; Hardcastle, 1973; Morris et al., 2008). The only inconsistency found here was that almost all of the above researchers have mentioned that uvular plosives have less VOT values than palatals; because the contact area between articulators is more in production of palatal plosives than in uvular plosives but it was not the case in the present study. In this paper, uvular plosives had positive VOTs; it may be due to the way uvular plosive is produced in Persian. Uvular plosives are produced both in voiced and voiceless forms in Persian depending on the region they are produced. This research was carried out in Kerman (a city of Iran) whose speakers pronounce uvular plosives fully and toughly voiceless. Thus, /q/ seems to have very high VOT values in this region.

Concerning F0 of onset of plosives, a significant difference was observed between the groups concerning front places of articulation (bilabial and alveolar plosives), but no significant difference was observed in back places of articulations (palatal and uvular plosives). The boys and girls did not show any significant differences in F0 of onset. According to Roohparvar et al. (2020), the insignificant effect of gender in this study and similar ones can be attributed to the fact that the participating boys and girls were before puberty age.

In order for hearing-impaired children to have a normal life and to communicate effectively, their speech comprehension and subsequently production must be improved. Regarding speech comprehension, some hearing aids have been designed to help them hear sounds which they were deprived of before. Concerning production, speech therapists have long been trying to teach them how to utter sounds and words. Considering the mentioned points the findings of this study would be beneficial to speech therapists, clinical linguists, and application designers in focusing on speech sounds which are challenging for HI children to produce.

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