


ORIGINAL ARTICLE

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Egyptian vowel second formant in isolation and in transition following high-frequency fricatives by NLFC hearing aid in children: how does the pattern compare to typically hearing peers?

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Abstract

Background: High-frequency consonants form an area of difficulty among children with hearing impairment. Many technological setups have emerged in order to improve their audibility, among them nonlinear frequency compression (NLFC). Therefore, the following study was carried out in order to evaluate change in production of high-frequency fricatives by hearing-impaired children utilizing NLFC hearing aids. This was through spectrographic analysis of F2 onset of transition elicited by fricatives in a prevocalic context, and results were compared to typically developing (TD) children. A change in mid-frequency sounds due to high-frequency compression was also tested through production of sustained vowels in isolation.

Results: A preliminary prospective case-control study involved 9 patients with NLFC hearing aids, evaluated at 1- and at 6-month post-fitting, without receiving speech therapy. Spectrographic analysis of F2 formant onset in [a] and [i] vowels when combined with [s] and [f] fricatives in a CV (consonant-vowel) pattern, presented auditorily and audio-visually, was observed and analyzed. One patient was excluded due to noncompliance in attendance. In the 8 patients who completed the study, very high-frequency level of F2 onset in CV was notable in second versus first evaluation in NLFC group, to the extent of surpassing the typical value in TD control group with [i] vowel. Contrastingly, F2 of sustained vowels in isolation took a trend of a lower value after 6 months of NLFC hearing aid use, as compared to the first evaluation. Consequently, the gap between sustained vowel F2 level in TD and NLFC groups widened.

Conclusion: Mean high-frequency range of F2 onset of transition in CV patterns of voiceless fricatives [s] and [f] with [i] and [a] vowels 6 months after NLFC fitting reflects an enhancement in the frequency range production of these sounds. A shift toward a lower F2 frequency range in sustained mid-frequency vowels, on the other hand, remains to be carefully investigated as a sequel of nonlinear frequency compression in the Egyptian hearing-impaired children.

Keywords: Nonlinear frequency compression, Hearing aids, Spectrographic analysis, Fricatives, Formant transition onset

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Background

The high-frequency range in the speech spectrum is a tricky area, not only for the hearing impaired but also for the typically hearing as amplitude thresholds tend

be lower above 2 KHz. This is an important area for normal speech development and a problematic area for good audibility by the hearing aids [1]. In some hearing-impaired children, sounds in the high-frequency range defy perception by conventional amplification, which as a consequence paved the way to frequency lowering hearing aid technology.

Frequency lowering hearing aids reduce the problem of abruptly falling high-frequency hearing loss. They shift or compress high-frequency sounds into a lower frequency range, thus making previously undetectable high-frequency sounds perceptible to the hearing-impaired listener [2]. In infants and young children, the loss of audibility of high-frequency sounds compromises speech understanding by preventing the proper perception of many of the high-frequency voiceless consonants. Currently available approaches for frequency lowering in wearable hearing aids include nonlinear frequency compression (NLFC) [3], linear frequency transposition (LFT) [4], and spectral envelope warping [5].

In NLFC, the incoming hearing aid signal is split into two channels. The high-frequency channel is compressed into a narrower bandwidth resulting in sound being lowered in frequency within the high-frequency channel. An adjustable cutoff frequency between the high and low bands and an adjustable frequency compression ratio in the high band is present [3]. NLFC is a relatively new and substantially expensive technology in Egypt, with no research to date covering its effect on high-frequency fricatives and mid-frequency vowels production, as speculations about the effect of high-frequency migration to mid-frequency range containing second formants of vowels were raised earlier by Alexander [5]. Previous regional research in this domain addressed perception of high-frequency consonants after NLFC fitting [6, 7].

Spectrograms are acoustic tools that provide visual presentations of speech sounds, consonants and vowels, and their interactions. Consonants are largely distinguished by the effect they produce on the formants of the adjacent vowels, a phenomenon called formant transition. Formants are elevations in the intensity of some harmonics in the frequency spectrum created by resonances in the vocal tract [8]. The first two formant frequencies (F1 and F2) demarcate the characteristic vowel quality and constitute the crucial differentiator between vowels [9]. They are the identity cards for each vowel; hence, they play an important role in speech recognition. Changes in the position of articulators between consonants and vowels will modify the cavity shape of the vocal tract and cause a transition in formant frequencies, by either lowering or elevating them. Transition of the first formant (F1) is related to manner of articulation, while transition of the second

formant (F2) is a spectrographic acoustic cue for consonant place of articulation. The first part of the vowel transition is the vowel onset which contains important acoustic information pertaining to the vowel place feature [10]. Children were found to pay more attention to the formant-onset frequency of the vowel and less attention to the dynamic formant transition when identifying a vowel [11].

Fricatives are speech sounds located mostly in the high-frequency range and are specifically challenging for the hearing impaired, although they greatly affect speech intelligibility. They are produced with a narrow constriction in the oral cavity. The turbulence of the airflow passing this constriction generates the characteristic sound of frication. The exact location of the narrow passage and the size and form of the cavity in front of the constriction define the acoustic characteristics of the fricative [12]. The energy peaks in a fricative's spectrum serve listeners as primary cues for fricative identification. Nevertheless, in addition to analysis of spectral pattern of fricatives (frication noise together with location, amplitude, and duration of the noise); formant transition into the following vowel in a CV (consonant-vowel) pattern was also used in fricatives' study [13]. Formant transitions have been reported to play a role in identification of some fricatives. This is language specific and depends on the presence of spectrally similar fricatives in the listener's native phoneme inventory [14]. The greater the number of fricatives in a language, the higher the possibility of the presence of spectrally similar fricatives. The Egyptian language has multiple fricatives in the phoneme inventory, with back and emphatic fricatives in addition to the English-similar ones [15].

Fricatives in Egyptian phonology extend in frequency ranges of 2–5 KHz (/f/, /x/, /ɣ/, /h/, /ʕ/, /ħ/) and of 4–8 KHz (/s/, /ṣ/, /z/, /ʔ/) [6]. These fricatives scan the vocal tract from the labiodental (/f/) to the alveolar (/s/, /ṣ/, /z/), palatal (/ʃ/), velar (/x/, /ɣ/), pharyngeal (/ħ/, /ʕ/), and finally the glottal domains (/h/). The migration of a multitude of high-frequency fricatives to a relatively compressed mid-frequency zone, under the effect of NLFC hearing aids, would render it interesting to investigate how migrating high-frequency and mid-frequency sounds would be produced under this new technology. The idea of this research, hence, emerged from the perspective of Egyptian phonology, an Arabic language unique and diverse in its phonemes.

The objective of this study is to answer the following questions:

- 1) Is second formants' F2 mid-frequency range affected in sustained vowels after NLFC hearing aid use in Egyptian children for 6 months?

- 2) Is second formants' F2 onset altered in high-frequency fricative-vowel combinations following NLFC hearing aid use in Egyptian children for 6 months?
- 3) How do both patterns compare to productions by typically developing Egyptian children?

Methods

The study included a hearing-impaired patient group (HI) and a control typically developing group (TD). The HI group contained nine patients, in the age range between 6 and 18 years. They had bilateral severe-to-profound sensorineural hearing loss of the high-frequency configuration distorting the perception of the high-frequency speech elements or sounds. There was lack of benefit from the conventional amplification in the high-frequency range (dead zones in the cochlea), and a frequency lowering technology was indicated. They have been fit with Unitro Max 20 behind the ear hearing aids, utilizing frequency lowering NLFC technology. They were selected according to specific selection criteria, which included an IQ equal to or higher than 90 (Stanford-Binet test — Fifth Edition), a regular hearing aid use since diagnosis, together with compliant supportive parents, who attended their appointments regularly and were looking for new technology in the hearing aids. Patients and their parents were informed about the objectives of the study, and a written consent was obtained from each participant or one of his/her parents. The TD group contained 30 children of matching age.

Hearing aid adjustment was done as suggested by the software default. The cutoff frequency was kept at the last frequency on the audiogram with remaining hearing thresholds. The compression ratio was adjusted to the lowest value in all subjects to minimize the distortion in speech elements as a result of using NLFC. The cutoff frequency ranged from 2.3 to 3 KHz after analysis, with 1.2 compression ratio for each patient. In the audiology unit, patients were followed up at 3-month interval through aided sound field and Arabic speech perception. In the phoniatric unit, evaluation was done twice at 1- and 6-month post-fitting, according to a planned protocol. The complete protocol was done during the first evaluation; while in the second one, only the additional instrumental measures were repeated. One patient was excluded due to attendance of only one evaluation. The results presented in this study are those done in the Phoniatric Unit.

(i) *Elementary diagnostic procedures*

They provided the database for each patient and included the following:

- a. Patient's interview which included the following: personal history (name, age, sex) and history of hearing impairment (onset, course, duration) and of any speech/language therapy received.
- b. Assessment of language in a naturalistic context to provide data of sentence length, structure, and narrative skills.

(ii) *Additional instrumental measures*

These went through acoustic and spectrographic analysis of second formant (F2), first from sustained vowels /i/ and /a/ in isolation by Sona-Match (Model 4327) of Kay Elemetrics and then from F2 onset in vowels /i/ and /a/ following high-frequency voiceless /s/ and /f/ fricatives in a consonant-vowel context (CV). The (CV) combinations were presented to the patient once auditorily and then audio-visually in a quiet soundproof room. The patient (study group) or TD child (control group) was instructed to repeat the same utterance (sustained vowel /i/, /a/ and consonant-vowel /sa/, /si/ and /fa/, /fi/) in front of a Carol MUD-525 unidirectional dynamic microphone, with a low impedance of 600 Ω , placed 15 cm from his/her mouth and connected to the Computerized Speech Lab (CSL) system of KayPentax (model 4150). This is designed for speech acquisition and acoustic analysis, with a real-time spectrogram (model 5129) that captures and displays vowel-consonant combinations and isolated vowels. It is a fast Fourier transform (FFT) spectrogram, allowing for speed in waveform analysis. It is three dimensional, with frequency on the vertical axis, time on the horizontal axis, and energy expressed in darkness or color gradients. A waveform is displayed from which formant frequencies could be extracted.

The frequency level of F2 in sustained vowel and in F2 onset in CV syllable was documented from the following groups:

- Thirty typically developing (TD) children presented to them auditorily.
- Eight NLFC children at 1-month and 6-month post-fitting presented to them auditorily and then audio-visually.

The experiment was therefore a twofold study to obtain the following:

- F2 of sustained vowels /i/ and /a/
- F2 at vowel onset of /i/ and /a/ following high-frequency fricatives /s/ and /f/

The evaluation was done once in the control TD group to set a baseline for typical values, and twice in NLFC group, firstly to set a baseline for each child at

the beginning of NLFC fitting, and secondly to monitor change in F2 onset after 6 months of NLFC hearing aid use.

Statistical analysis could be summarized as follows:

- Microsoft Excel 2013 was used for data entry, and the Statistical Package for Social Science (SPSS version 24) was used for data analysis.
- The mean and standard deviations were used in describing data related to age, gender, and F2 frequency level. Percentages were used to compare the mean values in the study NLFC group, 1 and 6 months, post-fitting. The data were represented by bar charts.

Results

The current work is a prospective case-control study that examined the effect of frequency lowering of fricatives by NLFC technology on vowels' second formant frequency level in isolation and at onset of transition in /CV/ syllables. The study was completed on 8 out of 9 patients (4 females and 4 males), with age range between 6 and 18 years. The youngest was 6 years, 7 months; the oldest 17 years, 9 months; the mean age of the group 13.5 ± 3.5 years; of males 13.75 ± 4.1 years; and of females 13.25 ± 2.8 years. All children had satisfactory aided responses that were in the limit of the long-term average speech spectrum. This ensured the audibility of all sounds using the NLFC hearing aid and subsequently ensured the feasibility of all speech tests and spectrographic evaluation.

Recorded findings on F2 in sustained vowel production and in onset of transition in CV syllable after high-frequency fricatives in TD and NLFC children

1) F2 in sustained vowels [i] and [a]:

- Table 1 shows the mean and standard deviation values of F2 of sustained /i/ vowel, in both control TD and study NLFC group (two evaluations). The frequency level of F2 in NLFC hearing-impaired children was less than the recorded level for typical children in both evaluations. The mean value decreased, however, in the second evaluation after using NLFC hearing aid for 6 months, in both auditory and audiovisual presentations. No notable difference was recorded in F2 level between these two modes of signal presentation.
- Table 2 presents the same type of data as in Table 1 but for vowel [a]. It is also evident that F2 level was less in the hearing-impaired children compared to the control group of typically developing children. It is notable that the auditory mode of presentation in the first evaluation yielded a slim difference in F2 level between the TD and NLFC groups, although following the same pattern of a smaller value in NLFC group. After 6 months, the difference between the lower value of F2 in NLFC group and the standard value in TD group was notable. Again, the values in both modes of presentation were comparable.

2) F2 onset in CV syllables /si/, fi/, /sa/, and /fa/:

Table 1 F2 of sustained [i] vowel in TD and NLFC groups

TD		NLFC	
		Auditory	Visual
2807.83 Hz (\pm 392.3)	1st assessment	2297.63 Hz (\pm 690.96)	2342.63 Hz (\pm 701.56)
	2nd assessment	2073.13 Hz (\pm 478.5)	2096.63 Hz (\pm 527.86)

Table 2 F2 of sustained [a] vowel in TD and NLFC groups

TD		NLFC	
		Auditory	Visual
2167.17 Hz (\pm 351.17)	1st assessment	2096.13 Hz (\pm 525.66)	1741.13 Hz (\pm 383.43)
	2nd assessment	1539.38 Hz (\pm 301.27)	1486 Hz (\pm 288.59)

Table 3 Mean of F2 onset in /si/ syllable in TD and NLFC groups

TD		NLFC	
		Auditory	Visual
7504.9 Hz (\pm 1125.35)	1st assessment	4820.63 Hz (\pm 3848.31)	4416.75 Hz (\pm 3275.59)
	2nd assessment	10504.25 Hz (\pm 5146.04)	7932.88 Hz (\pm 3702.97)

Table 4 Mean of F2 onset in /fi/ syllable in TD and NLFC groups

TD		NLFC	
		Auditory	Visual
7913.6 Hz (\pm 1855.93)	1st assessment	5080.5 Hz (\pm 4824.71)	5066.13 Hz (\pm 4014.49)
	2nd assessment	8733.4 Hz (\pm 4658.15)	8874.63 Hz (\pm 5064.23)

Table 5 Mean of F2 onset in /sa/ syllable in TD and NLFC groups

TD		NLFC	
		Auditory	Visual
7075.5 Hz (\pm 2253.2)	1st assessment	6029.88 Hz (\pm 7778.78)	3254.13 Hz (\pm 2414.93)
	2nd assessment	5990.13 Hz (\pm 2064.5)	5937.25 Hz (\pm 1457.66)

Table 6 Mean of F2 onset in /fa/ syllable in TD and NLFC groups

TD		NLFC	
		Auditory	Visual
8431.67 Hz (\pm 3653.84)	1st assessment	3724.625 Hz (\pm 3595.28)	3160.13 Hz (\pm 3142.66)
	2nd assessment	5491.88 Hz (\pm 2093.86)	5632 Hz (\pm 1792.68)

- Table 3 shows the F2 onset values in /si/ syllable. A noteworthy difference in F2 onset is seen between TD and NLFC children in both auditory and audiovisual presentations in the first evaluation. The latter two values are very comparable. A marked increase in F2 onset in the second evaluation 6 months after NLFC use has rendered the F2 onset mean value to be higher than that in TD group, with a more pronounced increase in the auditory group.
- Table 4 shows F2 onset values in /fi/ syllable. The values of F2 onset in NLFC group which were markedly lower than the values of TD group in the first evaluation have soared in the second evaluation after 6 months of NLFC use, to be higher than the mean value reported in TD children.
- Table 5 displays the values of F2 onset when the prevocalic fricative /s/ combines with [a] vowel. The values of F2 in the first evaluation of NLFC group were both below the level of F2 in TD children. There were, however, discrepancies between auditory and audiovisual mean values, with the auditory level nearly double the audiovisual level. In the second evaluation, level of F2 increased in both modes of presentation, with very comparable values.
- Table 6, showing mean F2 onset values in /fa/ syllable in the two groups of TD and NLFC, clearly displayed lower F2 values in NLFC's two evaluations as compared to TD group. The second evaluation in NLFC has, however, shown higher levels of F2 onset compared to the first evaluation, with comparable values in

auditory and audiovisual presentations in both evaluations. In tables (1–6), it is evident from the standard deviation values that variability in F2 levels of vowels existed, in isolation and in onset of transition, even among the typically developing children.

- 3) F2 of sustained vowels [i] and [a] versus F2 onset of transition in CV syllables /si/, /fi/, /sa/, and /fa/:

Comparisons were done putting in consideration to disclose F2 of the sustained Egyptian /i/ and /a/ vowels in isolation and in the onset of transition following /s/ and /f/ high-frequency consonants for TD during a single assessment and NLFC child in two assessments 1 and 6 months after hearing aid fitting. The results were recorded in the following figures:

- A) Figure 1 bar chart displays the mean of the previous values as per vowel [i] in TD children. Out of the 30 TD children, 17 had higher F2 onset in /fi/ as compared to /si/. Accordingly, the mean value of F2 onset in /fi/ was higher than in /si/. Variability was noted across the 30 children, in spite of the fact that the children were typically developing children with normal hearing and language abilities.
- B) Figure 2 displays the mean of these values as per vowel [a] in a bar chart. Out of 30 TD children, 21

had higher F2 onset in /fa/ as compared to /sa/, which was reflected on the difference in the mean values as shown in the figure.

- C) Figures 3 and 4 show a bar chart complex of 12 readings of F2 mean in [i] versus F2 onset in /si/ and /fi/, and F2 mean in [a] versus F2 onset in /sa/ and /fa/ in the auditory and audio-visual presentations, during first and second evaluations in NLFC children. Other than a comparable level of F2 onset in the two evaluations, F2 level in isolated vowels decreased, and F2 onset level increased in the second evaluation across all fricative-vowel combinations.

- 4) Percentage of change in F2 frequency in NLFC study group in second evaluation as compared to first evaluation:

Table 7 shows percent change (lower or higher) in all parameters in the second compared to the first evaluation in NLFC study group. These parameters are as follows:

- F2 in sustained [i] and [a] vowels: All F2 frequency levels of [i] and [a] decreased in the second evaluation in the study group after 6 months of NLFC use, both in auditory and audiovisual inputs. This was more notable in [a] than in [i].

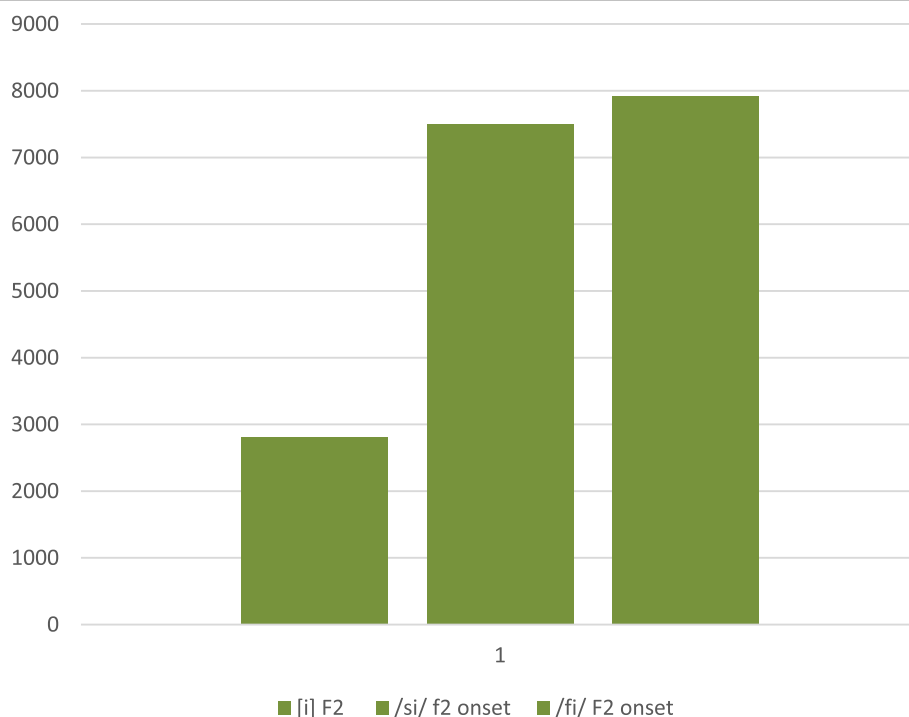


Fig. 1 Mean F2 for [i] and mean F2 onset for /si/ and /fi/ in TD children

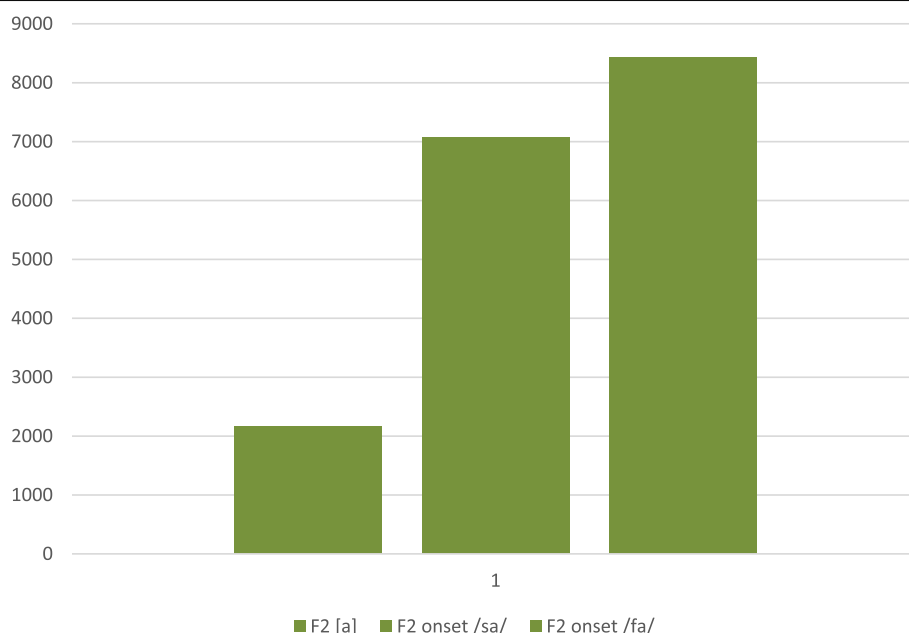


Fig. 2 Mean F2 of [a] and mean F2 onset in /sa/ and /fa/ in TD children

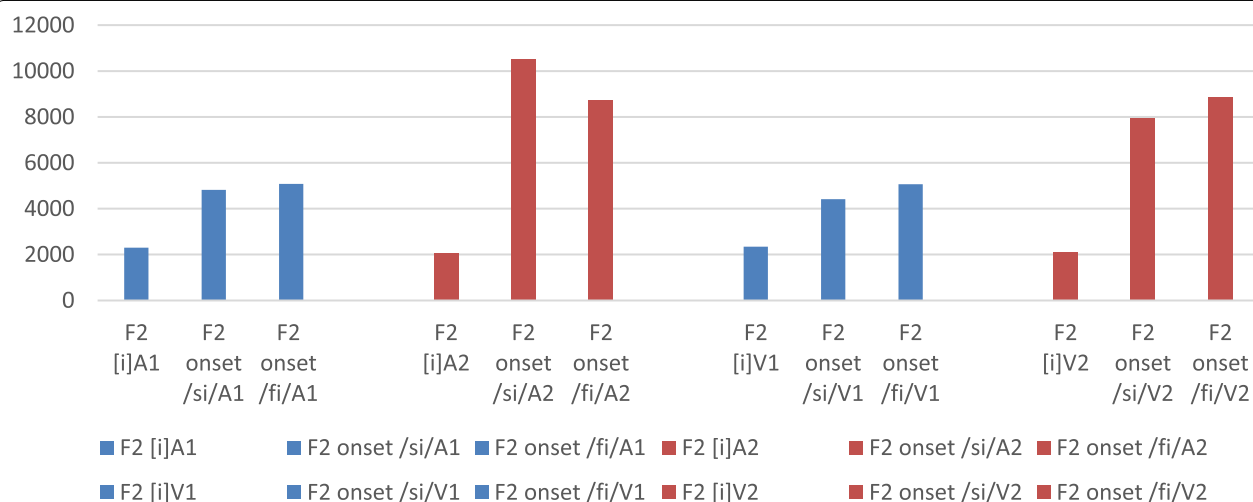


Fig. 3 Mean F2 in [i] and mean F2 onset in /si/ and /fi/ in audio and audiovisual presentations, 1 month and 6 months after NLFC fitting. A, audio presentation. V, audiovisual presentation. 1, first evaluation 1 month after NLFC fitting (blue). 2, second evaluation 6 months after NLFC fitting (red)

- F2 onset of transition with vowel [i] in /si/ and /fi/: There was increase in F2 onset value in second evaluation, more in auditory than audiovisual mode of presentation with /si/ and at a comparable level between both modes with /fi/.
- F2 onset of transition with vowel [a] in /sa/ and /fa/: There was also increase in F2 onset values with /sa/ and /fa/ in the second evaluation in NLFC group, except with /sa/ in the auditory mode of presentation.

Discussion

Vowels are relatively static portions of speech that do not require movement of articulators as the dynamic fricative consonants. Vowels require an open vocal tract that allows resonance, which gives birth to intensified frequencies called formants. The transformation to the static from the dynamic speech sector is accompanied by a change in formant frequency of the vowel, called transition. Transition of second formant is related to place of constriction in the consonant articulation.

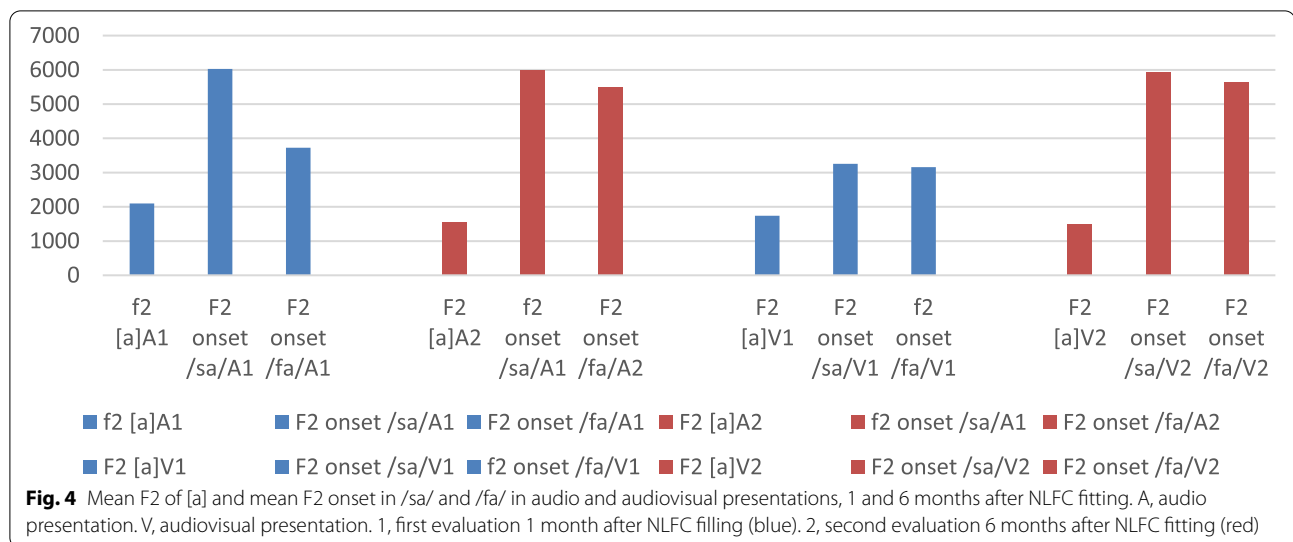


Table 7 Percent change in F2 of isolated [i] and [a] vowels and F2 onset in /si/, /fi/, /sa/, and /fa/ syllables in second compared to first evaluation in NLFC group

Name of parameter studied for percent difference	Auditory	Audio-visual
F2 in sustained [i]	9.77% lower	10.5% lower
F2 in sustained [a]	26.6% lower	14.6% lower
F2 onset in /si/	117.9% higher	79.6% higher
F2 onset in /fi/	71.9% higher	75% higher
F2 onset in /sa/	0.66% lower	82.5% higher
F2 onset in /fa/	47.5% higher	78% higher

Consonants need a neighboring vowel to make them perceptible, audible, and vivid. This is through formant transition, which is equally important in perception and production of vowels. Although formants of sustained isolated vowels and formant transitions in consonant-vowel combinations are not consistent, yet the detection of a slope pattern in the formant frequencies in CV combinations indicates that the articulators are actively moving to access different speech targets. As the objective of the present study was to detect the change in F2 in the vicinity of the high frequency, NLFC modulated fricatives /s/ and /f/; the focus was on the onset of the F2 transition in comparison with the static form of F2 of vowels /i/ and /a/.

The cut off frequency in the present research was at a range between 2.3 and 3 KHz. In a previous study, F2 of /i/ in Egyptian children was found to be 2605 Hz \pm 443, and that of /a/ was 2022 Hz \pm 478 [16], with comparable values in the present study (Tables 1 and 2). Both

studies included 30 typically developing children. The /i/ vowel is accordingly considered a challenge to hearing-impaired children due to the high value of second formant. As for fricatives, the peak frequency of /s/ was reported in children to be between 6300 and 8300 Hz [17]. The peak frequencies were also reported to be 3.8–8.5 kHz for /s/ [18] and to be around 6.5 KHz for nonsibilant /f/ [19]. Furthermore, values of /s/ and /f/ fricatives were reported by Ahmed et al. [6] to be between 4 and 8 KHz. Accordingly, F2 of /i/ was predominantly affected by frequency lowering, according to the level in each individual child, unlike F2 of /a/ which fell mostly below the cutoff frequency. NLFC technology, on the other hand, caused consistent frequency reduction of /s/ and /f/ in all children.

From a phonological point of view, each sound has its own unique set of distinctive features that are both articulatory and acoustic in origin. The acoustic part was altered by NLFC technology, in order to render an inaudible phoneme audible. Besides the new conglomeration of distinctive features when pronounced in a solitary form, each phoneme is affected by the neighboring phonemes in a connected speech form. Both the high-frequency fricatives and mid-frequency vowels underwent alterations in their positions on the spectrum map due to frequency transposition technology.

Limitations of the present study and measures taken for their control

The number of patients in the study group is 8 children, although the study extended for about 3 years to be able to obtain a sample size that would allow tests of significance. The original number of patients included over this period was 9, but one patient was

excluded due to noncompliance. The high-frequency sloping audiogram that does not respond to conventional hearing aids in the high-frequency region and requires frequency lowering technology is quite infrequent among the hearing-impaired population. Added to this is the substantially expensive cost of the NLFC hearing aids.

As a counter strategy to the small number of patients, 12 samples were taken from each patient. Each patient was required to utter sustained /i/ and /a/ vowels and /sa/, /si/, /fa/, and /fi/ syllables, upon hearing them auditorily and audio-visually. This provided a vast number of data, which nevertheless could not be grouped together because they are independent variables. Analyzing each set of data separately in the form of descriptive statistics (means and standard deviations), while displaying them in tables and bar charts, allowed for observation of multiple trends occurring after using NLFC hearing aids for 6 months, versus the typical occurrence in TD children. Furthermore, percentage of increase or decrease of F2 in sustained vowels and CV syllables in the second evaluation within the NLFC group added more insight to the results. No tests of significance were done due to the small number of the NLFC group. The data presented preliminary evaluation of the outcome of using NLFC hearing aids in the Egyptian population from the perspective of not only high- but also mid-frequency sounds. A sound data base for F2 in the typically developing Egyptian children in isolation and in transition was an important addition and could be used in future studies.

The trends obtained from the present study could be summarized as follows:

- 1) The F2 frequency in isolated mid-frequency vowels [i] and [a] followed a pattern of a lower frequency after the use of NLFC technology, evident in second evaluation as compared to first evaluation in NLFC group and to TD group.
- 2) The F2 frequency at onset of transition in CV syllables /si/, /fi/, /sa/, and /fa/ experienced a rise in second evaluation of NLFC group, except a slight decrease in /sa/ in the auditory mode. This rise was more evident in [i] vowel, so that it surpassed the F2 onset frequency in TD group.
- 3) The results obtained through auditory and audiovisual modes of presentation were mostly comparable. Discrepancies occurred in relation to [a] vowel in isolation and in CV syllables containing [s] consonant.

Mid-frequency range change after NLFC technology

This was represented by F2 of sustained [a] and [i] vowels. It was noted that F2 value migrated to a lower value in NLFC hearing aid children, 6 months compared to 1-month post-fitting, both in auditory and audiovisual modes. This denoted a shift toward a lower frequency in the mid-range. Previous research has questioned vowel perception in NLFC, and that it could be decreased depending on the degree of compression [20]. In the current research, vowel F2 in NLFC consistently parted from the typical level toward a lower frequency range.

High-frequency range change after NLFC technology

There was an increase in frequency of F2 onset of transition in all CV combinations in the second evaluation in NLFC children, except in /sa/, which decreased slightly by 0.66%. The new mean value was lower than the typical mean F2 onset value with [a] vowel in TD children but superseded the typical F2 onset value in [i] vowel. This suggested a shift in the high-frequency production of voiceless fricatives [s] and [f] toward the typical value in TD children. The rise in F2 onset frequency was more pronounced when grouped with [i] vowel.

How auditory mode of presentation compares to audiovisual mode

Both modes of presentation did not show discrepancy in the majority of recordings. Contrary to expectations, the NLFC children's productions following both modes of presentation were comparable. It was noted that when discrepancies occurred, they were related to [a] vowel and [sa] consonant in CV syllables in the first evaluation. This however changed in the second evaluation, and this is a positive finding. On the other hand, the F2 onset value in /si/ syllable was disparate in the second evaluation between auditory and audiovisual modes. Both however took the same trend, which is an increase from the original value in the first evaluation. According to Jerger et al. [21], the visual speech fills in the missing information by non-intact auditory speech, and so the values through audiovisual channel are considered more informative.

From the audiological perspective, studies evaluating the effects of NLFC algorithms on speech perception and sound quality revealed variability in benefit across subjects [22]. Studies showing some benefit [23] found that NLFC improves identification of high-frequency consonant sounds. These sounds defy perception with conventional technology due to nonfunctioning inner hair cells, or dead regions, within portions of the cochlea where mechanical vibration of the basilar membrane is not properly transduced to electrical stimulation of auditory nerve. Other studies reported distortion of other speech

sounds, as an undesirable effect of this technology [24], especially the 2nd formant frequency [5].

As the spectral characteristics of the original input signal are altered, with a change in the original sound quality, an acclimatization period with auditory training was suggested in previous research in order to adapt to frequency compression technology [23]. This is where speech therapy comes in to complete the overall benefit from the device, but this was neither included nor monitored as an aim in the present study.

Conclusion

It could be summarized that acquisition of high-frequency fricatives, which occupy an important location in speech recognition, is a challenge to hearing-impaired children and hearing aid technology. Nonlinear frequency compression (NLFC) is a relatively new technology in Egypt. Spectrographic analysis of [i] and [a] F2 formant frequency in sustained vowel and when merged with voiceless fricatives /s/ and /f/ in CV sequences was observed and analyzed in this study. Variability across participants in CV formant onset both in TD and NLFC groups was met with a predominant consistent high frequency of F2 in second compared to first evaluation, more in /i/ vowel. A high-frequency range of F2 transition onset in vowels neighboring voiceless fricatives after NLFC technology was hence a notable finding. As a contrastive finding, F2 frequency level in sustained vowels decreased in the second evaluation after using NLFC for 6 months. Hence, the gap between F2 levels of sustained [i] and [a] for NLFC hearing impaired and TD control groups increased after 6 months of nonlinear frequency technology use.

Changing frequency spectrum of high-frequency fricatives from high to mid-range in order to switch them from inaudible to audible comes at the expense of modification of original distinctive features of these sounds. This artificial change affects mid-range vowel production, and vowels are the core of syllables. It is a conflict between consequences of hearing fricatives differently or not hearing them at all.

Abbreviations

NLFC: Nonlinear frequency compression; LFT: Linear frequency transposition; F1: First formant; F2: Second formant; CV: Consonant-vowel; TD: Typically developing; FFT: Fast Fourier transform; CSL: Computerized Speech Lab; SPSS: Statistical Package for Social Science.

Acknowledgements

Thanks are due to the participating hearing-impaired children and their parents for their compliance and patience.

Authors' contributions

MMS has a substantial contribution to the intellectual content, conception, and design of this work. She participated in literature review. She contributed to data analysis and interpretation. She wrote the

manuscript. She agreed to be the corresponding author and the guarantor of this work. HOM has a substantial contribution to the literature review and made the clinical study. She collected data and contributed to data analysis and interpretation. IE has a considerable contribution to the study design and the intellectual content. She participated in data interpretation. DH has a significant contribution to the study design and the intellectual content. She participated in the study design, was the audiologist who selected the patients, and adjusted their NLFC hearing aids. She followed them up, revised the manuscript, and made a valuable editing. ST has a valuable contribution to the intellectual content, conception, and design of this work. She participated in data analysis. DAE has a substantial contribution to the clinical study design and discussions. She participated in data collection and was responsible for data tabulation, analysis, and interpretation. The authors read and approved the final manuscript.

Funding

There was no funding for spectrographic assessment in the Phoniatric Unit, but the NLFC hearing aids were provided to the Audiological Unit by El Nahar Hearing in Cairo.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Consent of publication

Not applicable

Ethics approval and consent to participate

The current work was conducted in accordance to the guidelines of the Research Ethical Committee of Faculty of Medicine Ain-Shams University after receiving the committee's approval. The research received the ethical approval of the Research Ethical Committee of Faculty of Postgraduate Childhood Studies, Ain Shams University (Approval No. RHDIRB2020110401/4/2022). Patients and their parents were informed about the objectives of the study, and a written consent was obtained from each participant or one of his/her parents.

Competing interests

The authors declare that they have no competing interests.

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Received: 20 April 2022 Accepted: 15 July 2022

Published online: 30 July 2022

References

- Pittman A, Stelmachowicz GD, Lewis D, Hoover B (2003) Spectral characteristics of speech at the ear: implications for amplification in children. *J Speech Language Hear Res* 46(3):649–657. [https://doi.org/10.1044/1092-4388\(2003/051\)](https://doi.org/10.1044/1092-4388(2003/051))
- McCreery RW, Venediktov RA, Coleman JJ, Leech HM (2012) An evidence-based systematic review of frequency lowering in hearing aids for school-age children with hearing loss. *Am J Audiol* 21(2):313–328. [https://doi.org/10.1044/1059-0889\(2012/12-0015\)](https://doi.org/10.1044/1059-0889(2012/12-0015))
- Simpson A, Hersbach AA, Mcdermott HJ (2006) Frequency-compression outcomes in listeners with steeply sloping audiograms. *Int J Audiol* 45(11):619–629. <https://doi.org/10.1080/14992020600825508>
- Korhonen P, Kuk F (2008) Use of linear frequency transposition in simulated hearing loss. *J Am Acad Audiol* 19(08):639–650. <https://doi.org/10.3766/jaaa.19.8.7>

5. Alexander J (2013) Individual variability in recognition of frequency-lowered speech. *Sem Hear* 34(03):253–254. <https://doi.org/10.1055/s-0033-1348021>
6. Ahmed RA, Mourad MI, El-Banna MM, Talaat MA (2015) Effect of frequency lowering and auditory training on speech perception outcome. *Egypt J Otolaryngol* 31:244–249. <https://doi.org/10.4103/1012-5574.168360>
7. Ismael NM, Nada EH, El-Gharieb AM (2018) Comparison of three different frequency-lowering technologies in Arabic speaking hearing loss children. *Egypt J Otolaryngol* 34:145–154. https://doi.org/10.4103/ejo.ejo_51_17
8. Johnson K (2011) *Acoustic and Auditory Phonetics* (3rd). Wiley-Blackwell. ISBN-13: 978-1405194662.
9. Hillenbrand J, Getty LA, Clark MJ, Wheeler K (1995) Acoustic characteristics of American English vowels. *J Acoustic Soc Am* 97(5):3099–3111. <https://doi.org/10.1121/1.411872>
10. Sussman HM (1990) Acoustic correlates of the front/back distinction: a comparison of transition onset versus steady state. *J. Acoust. Soc. Am.* 88:87–96. <https://doi.org/10.1121/1.399848> [PubMed] [CrossRef] [Google Scholar]
11. Ohde RN (2011) German SR (2011) Formant onsets and formant transitions as developmental cues to vowel perception. *J Acoust Soc Am.* 130(3):1628–1642. <https://doi.org/10.1121/1.3596461>
12. Stevens KN (1998) *Acoustic phonetics*. MIT press
13. Jongman A, Wayland R, Wong S (2000) Acoustic characteristics of English fricatives. *J Acoustic Soc Am* 108(3):1252. <https://doi.org/10.1121/1.1288413>
14. Wagner A, Ernestus M, Cutler A (2006) Formant transitions in fricative identification: the role of native fricative inventory. *J Acoustic Soc Am* 120(4):2267–2277. <https://doi.org/10.1121/1.2335422>
15. Saleh M, Shoeib R, Hegazi M, Ali P (2007) Early phonological development in Arabic Egyptian children: 12–30 months. *Folia Phoniatrica et Logopaedica* 59(5):234–240. <https://doi.org/10.1159/000104461>
16. Khattab AN, Saleh MM, Hegazi MA, Hafez NG (2004) *Acoustic Analysis of Sustained Vowel Production in Egyptians with Cairene Dialect* [Unpublished master's dissertation]. Phoniatric Unit, Department of Otolaryngology, Ain Shams University, Cairo, Egypt
17. Stelmachowicz PG, Lewis DE, Choi S, Hoover B (2007) Effect of stimulus bandwidth on auditory skills in normal-hearing and hearing-impaired children. *Ear Hear* 28(4):483–494
18. Reidy PF (2016) Spectral dynamics of sibilant fricatives are contrastive and language specific. *J Acoustic Soc Am* 140(4):2518–2529. <https://doi.org/10.1121/1.4964510>
19. Maniwa K, Jongman A, Wade T (2008) Perception of clear English fricatives by normal-hearing and simulated hearing-impaired listeners. *J. Acoust. Soc. Am.* 123:1114–1125
20. Perreau AE, Bentler RA, Tyler RS (2013) The contribution of a frequency-compression hearing aid to contralateral cochlear implant performance. *J. Am. Acad. Audiol.* 24(2):105–120. <https://doi.org/10.3766/jaaa.24.2.4>
21. Jerger S, Damian MF, McAlpine RP, Abdi H (2017) Visual speech alters the discrimination and identification of nonintact auditory speech in children with hearing loss. *Int J Pediatr Otorhinolaryngol* 94:127–137. <https://doi.org/10.1016/j.ijporl.2017.01.009>
22. Hillock-Dunn A, Buss E, Duncan N, Roush PA, Leibold LJ (2014) Effects of nonlinear frequency compression on speech identification in children with hearing loss. *Ear Hear* 35(3):353–365. <https://doi.org/10.1097/aud.0000000000000027>
23. Ellis RJ, Munro KJ (2014) Benefit from, and acclimatization to, frequency compression hearing aids in experienced adult hearing-aid users. *Int J Audiol* 54(1):37–47. <https://doi.org/10.3109/14992027.2014.948217>
24. McDermott HJ (2011) A technical comparison of digital frequency-lowering algorithms available in two current hearing aids. *PLoS One* 6(7):e22358. <https://doi.org/10.1371/journal.pone.0022358>

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