The Hebrew Vowel System: Raw and Normalized Acoustic Data *

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KEY WORDS

bark

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ABSTRACT

It is well known that different languages use different vowel systems in terms of variety and number. The Hebrew vowel system consists of five vowels /i, e, a, o, u/. The present research identified the acoustic features of the vowels produced by Hebrew speakers differing in age and sex. Ninety speakers (men, women, boys, and girls) were recorded. The vowels were presented in a nonword context that was placed in a meaningful Hebrew sentence. The data included measurements of F0, F1, F2, F3, F4, and vowel duration for the five different vowels produced by the four groups of participants. Conversion of the physical frequency measures of formants into a critical band (bark) scale was performed as well. The results indicated that the F2/F1 ratio is a distinctive feature of all five vowels, keeping with the findings of previous research in other languages. Nevertheless, the values of the F2/F1 ratios led to an overlap between different vowels produced by different groups of speakers. Applying the bark transformation as speaker normalization procedure succeeded in reducing speaker differences while increasing vowel differences.

INTRODUCTION

The Israeli Hebrew vowel system consists of five vowels: /i, e, a, o, u/ (Chen, 1972). Previous research examined the articulatory characteristics of these vowels, with /i/ being described as a high front vowel, /u/ as a high back vowel, the /e/ as a midfront vowel, the /o/ as a midback vowel, and the /a/ as a low and central vowel (Laufer, 1983). All the Hebrew vowels are voiced, non-nasal, and their duration is not considered as a phonemic contrast (Chen, 1972).

Acoustic investigation of these vowels was previously performed using only a limited number of subjects (Laufer, 1981; Shwartswald, 1972). The purpose of the present research was (1) to describe the acoustic characteristics of the vowels produced by Hebrew speakers differing in age and gender, and (2) to apply the bark-scale procedure on the data in an attempt to speaker normalize the acoustic data.

METHOD

Participants

Four groups of speakers participated in the present study. Participants differing in age (children, adults) and gender were selected in order to get representative data of Hebrew

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speakers. Group 1 consisted of 30 men, mean age=25.3 years (*SD*=5.6), Group 2 consisted of 30 women, mean age=28.2 years (*SD*=5.9). Group 3 consisted of 30 children, mean age=9.0 years. This group was divided into two subgroups: 15 boys, mean age=9.0 years (*SD*=0.9), and 15 girls, mean age=9.0 years (*SD*=1.1). The age of 9 years was chosen in order to avoid including participants that have entered the phase of sexual maturation. The decision to include boys and girls in this group was done in light of the fact that children at that age are not expected to demonstrate differences in their vocal characteristics (Bennett, 1981; Lee, Potamianos, & Narayanan, 1999). All participants were born in Israel, they were native Hebrew speakers, and they all spoke standard Hebrew. A certified speech-language pathologist evaluated their speech, language, and hearing, and all participants were found to be within the normal limits.

Stimulus materials

Five CVC nonword syllables served as the stimulus material. The beginning and the ending consonants were the bilabial voiceless stop /p/. These consonants were chosen because they have short transitional periods when coarticulated with vowels, thus have less effect on the vowel characteristics (Gay, 1978; Manuel, 1990; Manuel & Krakow, 1984; Oliver, Greenwood & Colman, 1993; Rakerd, Verbrugge, & Shankweiler, 1984). The Hebrew vowels /i, e, a, o, u/ were placed in the middle of the syllable. The syllables, in turn, were placed in the middle of a Hebrew carrier phrase: "The teacher wrote ___ on the board" (/hamora katva ___ al haluax/). We chose to use nonword syllables because there was no suitable meaningful minimal quintuplet available for all five vowels. A meaningful Hebrew sentence was used as a carrier phrase to ensure standard Hebrew pronunciation. The above procedure was adopted from previous studies (e.g., Bennett, 1981). In order to minimize the effect of reduced amplitude and reduced F0, which might occur at the end of the sentence, the stimulus syllable was placed in the middle of the sentence.

Procedure

The participants were introduced to the sentences before the recording. They were instructed to read the sentences at a normal speaking rate with no emphasis on the stimulus word. Each of the participants read the five sentences five times in a random order. Thus, each subject produced 25 sentences. The recording was done individually in a quiet room using a Panasonic RQ-2102 tape recorder and a directional dynamic microphone situated approximately 5–10 cm from the speaker's mouth at an angle of 90°.

The recordings were presented to seven native Hebrew speakers who were senior students at the Department of Communication Disorders at Tel-Aviv University. The listeners were asked to identify each of the stimulus vowels using a five-alternative closed set paradigm. Only vowels that were identified correctly by all seven listeners were used for the acoustic analysis. It should be noted that of the 2250 productions (5 vowels × 5 repetitions × 90 participants) only 20 items were eliminated. In addition, one speaker from the boys' group who was identified by six of the listeners as having an unusual voice quality, was excluded from the study. This procedure, of using subjective judgment in order to exclude productions that are not clearly identified, has been in common use (Kallail & Emanuel, 1984; Peterson & Barney, 1952; Rakerd, Verbrugge, & Shankweiler, 1984).

Acoustic analysis

The acoustic analysis was done using Ariel Corp.'s "Speech Station 1" (SS1) software on a PC. Each stimulus vowel underwent the following analyses: fundamental frequency (F0), four formant frequencies (F1–F4), vowel duration, and relative amplitude of the vowel formants. All these values were measured in the middle of the steady state part of the vowel. In order to observe and measure the vowel formants, FFT and LPC analyses were performed. The FFT analysis was done through the use of a wide filter (128 samples hamming window length, at 10 kHz recording sampling rate) and the LPC analysis was done using 10–14 order (depending on the vowel), at a sampling rate of 10 kHz. The LPC and the FFT were displayed simultaneously on the computer monitor. The reported values were based, most times, on the LPC analysis. In cases where the formants were difficult to separate—for example, F1 and F2 in /u/ or F2 and F3 in /i/—the measures were made using the FFT technique. Moreover, when the FFT and the LPC values conflicted for a specific token, the measurements were not included. It should be noted that in some cases it was difficult to identify reliably the F3 or F4, especially in the children's productions. In those tokens only the lower formants were measured. Consequently, the total number of measurements for the higher formants was smaller by about 25% than that of the total number for the lower formants. Nevertheless, it should be noted that even after this data reduction, all measurements were based on a large corpus of data.

In order to measure vowel duration, the cursor was placed at both starting and ending points of the observed formant structure. The F0 was measured through the pitch analysis feature, which is an F0 extraction algorithm, built in the SS1 program based on an autocorrelation function. Since we did not compare the relative amplitude between vowels, only the frequency and duration values of the different vowels are presented here.

RESULTS AND DISCUSSION

Acoustic data

Table 1 presents the first four formant frequency values of the five Hebrew vowels that were measured for four groups of participants: men, women, boys, and girls. The data collected from the children's group is presented separately for the boys and the girls. Vowel duration values are presented as well. In this table, means and *SD* of each value are presented.

Using analysis of variance with repeated measures, the F1 and F2 values of the five vowels, collapsed over the groups, were found to differ significantly, $F(4,82)=733.63$, $p<.0001$; $F(4,82)=1676.46$, $p<.0001$, respectively). To examine the differences among the four groups with regard to each vowel, post-hoc multiple comparison tests (Einat & Gabriel's, 1975 analyses of variance) were performed yielding a significant difference among the groups ($p<.0001$). The men and women's groups differed in their F1 and F2 values in all cases except for the values of F2 for the vowels /o/ and /u/. F1 and F2 values of the girls were always significantly higher than those of the boys, except for the vowel /e/ where the trend was consistent although failed to reach significance.

Hebrew is traditionally viewed as a language that contains two high vowels /i, u/ and two mid vowels /e, o/. Inspection of the F1 values of these two pairs, which relates to vowel height, revealed practically no differences within each pair. For example, the

TABLE 1

Four formants frequencies (Hz) and duration (ms) values (means and SD) of the five Hebrew vowels produced by the four groups

		/i/		/e/		/a/		/o/		/u/	
		Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
	Men	342	(30)	455	(40)	626	(48)	478	(46)	359	(31)
	Women	381	(46)	548	(60)	859	(77)	542	(65)	411	(70)
F1	Boys	405	(58)	600	(68)	938	(105)	585	(78)	414	(53)
(Hz)	Girls	469	(70)	634	(82)	1041	(144)	656	(89)	477	(70)
	Men	2068	(142)	1662	(171)	1182	(90)	944	(105)	979	(91)
	Women	2555	(145)	2200	(172)	1560	(115)	988	(90)	824	(90)
F2	Boys	2828	(272)	2423	(191)	1665	(157)	1076	(137)	844	(149)
(Hz)	Girls	2968	(236)	2514	(177)	1925	(147)	1260	(170)	967	(139)
	Men	2562	(172)	2506	(156)	2417	(185)	2423	(173)	2445	(151)
	Women	2968	(147)	2912	(138)	2821	(245)	2892	(250)	2842	(374)
F3	Boys	3383	(219)	3339	(169)	3201	(284)	3284	(315)	3256	(360)
(Hz)	Girls	3594	(196)	3424	(172)	3304	(232)	3408	(249)	3411	(280)
	Men	3614	(210)	3623	(227)	3591	(223)	3450	(186)	3476	(203)
	Women	4220	(174)	4170	(213)	4109	(192)	4036	(236)	4100	(302)
F4	Boys	4369	(240)	4292	(183)	4223	(177)	4311	(228)	4413	(202)
(Hz)	Girls	4431	(269)	4365	(240)	4277	(142)	4351	(261)	4410	(314)
	Men	78	(18)	82	(16)	90	(19)	82	(18)	75	(21)
	Women	76	(15)	85	(15)	96	(15)	84	(17)	71	(15)
Dur.	Boys	93	(22)	103	(22)	114	(22)	114	(24)	102	(34)
(ms)	Girls	110	(31)	122	(46)	127	(32)	120	(30)	109	(30)

difference between the mean F1 values of the men's group between the two high vowels /u/ and /i/ was 17 Hz whereas the standard deviation for these measurements was 30 Hz. The difference between the F1 values of the men's group between the two mid vowels /o/ and /e/ was 23 Hz whereas the standard deviation for these measurements was close to 40 Hz. Similar results were observed for the other groups of speakers. Thus, it can be concluded that in the Hebrew vowel system there are three levels of vowel height: high, which includes /i/ and /u/; mid, which includes /e/ and /o/; and the low vowel /a/.

The F2/F1 ratio was calculated for each of the five vowels (Baken, 1987; Kent & Read, 1992; Lass, 1976; Peterson & Barney, 1952; Stevens, 1985). These ratios, collapsed over the groups were significantly different, $F(4,82)=760.02$, $p<.0001$. A profile contrast analysis conducted on all neighboring vowels yielded significant differences ($p<.0001$) in all contrasts.

Table 2 presents the F2/F1 ratios of the five vowels, as calculated for each of the groups. The table contains the F values of the differences between the groups as well.

As can be seen from the table, across all four groups each vowel was generally characterized by a similar F2/F1 ratio. While the ratios of the back vowels (/o, u/) as produced

TABLE 2

F2/F1 Ratio Values of the Five Vowels Expressed by the Four Groups (the results of the statistical analysis accompany the values)

Vowel	*Men*	*Women*	*Boys*	*Girls*	$F_{(3/85)}$
/i/	6.076	6.788	7.085	6.405	6.26**
/e/	3.675	4.046	4.068	4.039	5.18**
/a/	1.892	1.822	1.780	1.870	2.40
/o/	1.984	1.831	1.842	1.925	3.77*
/u/	2.217	2.024	2.037	2.050	4.12**

** $p<.01$; * $p<.05$

by the four groups were very similar, there was more variability among the F2/F1 ratios of the front vowels (/i, e/) as produced by the four groups. The F2/F1 ratios of the vowel /a/ were almost identical in the four groups.

Statistical analysis revealed that the ratios of the men's group were significantly different from those of the women for the vowels /i, e, o, u/. The ratios of the men were significantly different from those of the boys for the vowels /i, e, u/. The F2/F1 ratios of the boys and girls were similar in most cases except for the vowel /i/. For the values of the vowel /a/, however, there were no differences among the four groups.

Figure 1 presents the vowel centroids in the F1/F2-plane for the five vowels, for each of the four groups.

As can be seen from Figure 1, similar geometrical shapes were obtained for all four groups. The figure illustrates the expansion of the vowel space as an inverse function of vocal tract length, with back vowels remaining more stable than nonback vowels. The small differences between the four groups in F1 and F2 values of the back vowels might be explained by the mobility limitations of the tongue in the back of the oral cavity. The front of the oral cavity allows better and easier mobility of the articulators (Crothers, 1978), resulting in greater variability among speaker groups.

Observation of F1 values of the four groups revealed that the lower the vowel the greater the differences among groups (i.e., maximal differences were observed for the vowel /a/, while minimal differences were observed for the vowels /i, u/). For the F2 values of the four groups, however, maximal differences were observed for the front vowels (/i, e/) gradually diminishing towards the back vowels (/o, u/). Inspection of the F2/F1 ratios showed similar ratios for the four groups. While for the vowel /a/, no differences were found among the speaker groups, as the vowels became higher greater differences were observed among the groups. These differences were especially apparent for the front vowels.

It is apparent from Figure 1 that similar geometrical shapes were obtained for the F2/F1 ratios for the four groups. Nevertheless, while the geometrical shapes for three groups (women, boys, and girls) were close to each other, the men's group ratios were different. This difference led to an overlap between the frequency values of the mens' /o/ and the girls' /u/. Thus, these different vowels, when produced by different speakers had similar acoustic representation. An attempt to normalize these speaker differences will be presented later.

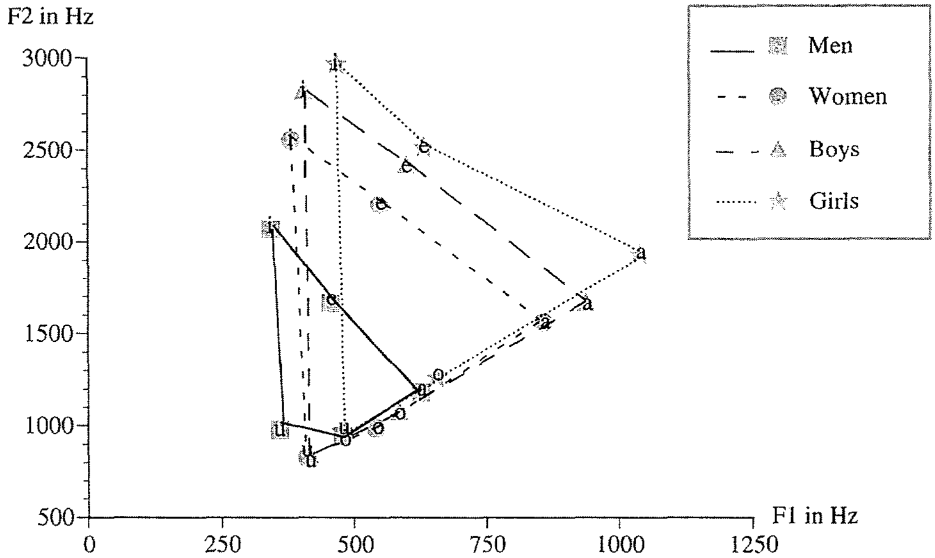

Figure 1

F2 values as a function of F1 values of the five Hebrew vowels produced by the four groups.

The following results were obtained with regard to F3 and F4 values, using the same statistical procedures described above. The F3 values of the five vowels collapsed over the four groups were significantly different, $F(4,82)=18.56$, $p<.0001$. In contrasting the values of the neighboring vowels (i-e, e-a, a-o, o-u), all vowels differed significantly from each other except for the pair /o/ and /u/. The F3 values of both sets of adults were significantly lower than those of the children. The F3 values of the women also were significantly higher than those of the men. There was no difference between the F3 values of the boys and the girls except for the vowel /i/.

The F4 values of the five vowels were also significantly different across all groups, $F(4,82)=12.02$, $p<.0001$. The neighboring vowels differed significantly except for /a/ and /o/. Adults' F4 values differed significantly from those of the children except for the vowels /e/ and /a/. Men's F4 values differed significantly from those of the women. There was no difference between the F4 values of the boys and those of the girls.

Figure 2 presents the vowel duration as a function of the five vowels. The figure presents data of the four groups of speakers: men, women, boys, and girls. Examination of the duration of the five vowels revealed that as vowel height decreased, vowel duration increased. These results support previous work by Lehiste (1970). The duration of the five vowels differed significantly across all groups, $F(4,82)=112.97$, $p<.0001$. All durations of neighboring vowels differed significantly from each other. In comparing vowel duration among the groups, no difference between the men's and the women's groups was found. The duration of the vowels produced by the adults was significantly shorter than that of the vowels produced by the children. It has been documented in previous studies that children's speaking rate and articulation rate are slower than that of adults (Chermak &

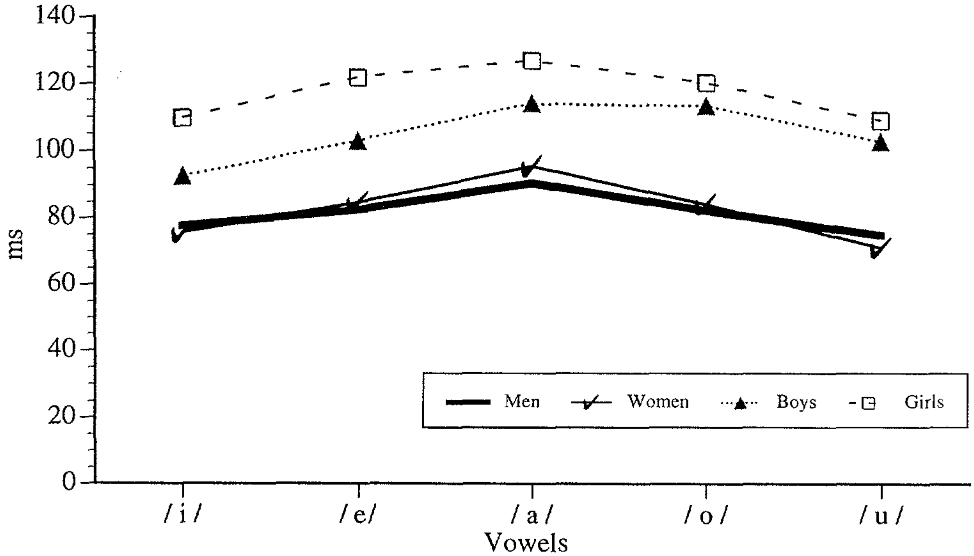

Figure 2

Vowel duration of the five vowels produced by the four groups of speakers.

Schneiderman, 1986; Kent & Forner, 1980; Starkweather, 1987). The results of the present study may be viewed as supporting these findings, although total utterance duration as an indication of speaking rate was not measured here. In general, there was a tendency for vowel duration to be longer for girls than for boys. These differences, however, failed to reach statistical significance in most cases. The vowels /i/ and /e/ were the only ones where statistical differences were found between the two children groups, that is, girls produced these two front vowels significantly longer than boys.

Although the five vowels were different with respect to their duration, vowel duration is not considered a phonemic contrast in Israeli Hebrew (Chen, 1972). The importance of the vowel duration to the perception of the Israeli Hebrew vowels should be further investigated in future research.

Table 3 presents the F0 mean values along with the standard deviations that were measured for each of the five vowels, in the four groups.

As can be seen in the table, F0 values decreased as vowel height decreased. According to the statistical analysis described above, the F0 values of the five vowels across the four groups were found to be significantly different, $F(4,82)=26.67$, $p<.0001$. In examining the F0 values of the neighboring vowels, all values were significantly different from each other except for the values of /e/ and /a/.

The F0 values of the adults were significantly lower than those of the children, and those of the men were significantly lower than those of the women. There was no difference between the F0 values of the boys and the girls. The similar F0 values that were exhibited by the boys and the girls are in agreement with the findings of F0 values of children before puberty reported in previous research (Bennett, 1981). Also, the F0 values of the different

TABLE 3

Mean F0 (Hz) and Standard Deviation of the five vowels produced by the four groups of speakers

	/i/	/e/	/a/	/o/	/u/
Men	142	136	134	141	146
SD	(30)	(25)	(24)	(26)	(30)
Women	219	207	203	210	222
SD	(31)	(33)	(26)	(27)	(38)
Boys	273	263	262	266	276
SD	(46)	(40)	(37)	(37)	(47)
Girls	266	257	254	259	270
SD	(42)	(35)	(34)	(32)	(40)

groups reported in the present study are in agreement with the range of values reported in the literature (e.g., Colton & Casper, 1990).

Although no differences were found between the F0 values of the boys and girls groups; significant differences were found between the two groups with regard to F1 and F2 frequencies. According to Lee, Potamianos, and Narayanan (1999), differences between English speaking male and female fundamental frequency and formant frequency patterns begin typically around the age of 11 and become fully established toward the age of 15. Our data suggest that formant frequency difference between males and females might be apparent even at earlier age (our children were close to the age of 9). While these differences cannot be explained anatomically in terms of larger larynx or larger vocal tract, they might provide some information about gender markers in different societies. Future research might shed more light on these possible cultural differences.

A comparison of the acoustic values of the Hebrew vowels to those of other languages may be of interest. Unfortunately, such comparison was technically complicated due to different methodologies, that is, different stimulus material, different number of speakers, and different procedures that were employed in each of these studies. For example, for the present study we used CVC syllables within a carrier phrase whereas in other studies on Shona (Pongweni, 1983) and Spanish (Delattre, 1969) vowels were produced in isolation.

Nevertheless, in a preliminary observation, we looked at the acoustic values of vowels of different languages. We looked at languages like English (Peterson & Barney, 1952), Russian (Fant, 1970), and Maithili (Jha, 1986) which contain a greater number of vowels. We also examined languages like Shona (Pongweni, 1983) and Spanish (Delattre, 1969) with an identical number of vowels as in Hebrew. Although not quantitative, this preliminary investigation seemed to indicate that the same phonetic symbol may be used to characterize particular vowels in different languages. The acoustic values that are expressed in one language cannot be assumed to apply for another language. These results support previous results by Disner (1983). Future research may examine the perception of vowels of one language by participants with different language backgrounds.

The differences among the different languages were mainly manifested in the values of F1. This was observed, in particular, in the F1 values of the high-front vowels. As the vowel became lower the differences among the languages, like the differences among the Hebrew speaker groups, became less pronounced. It seems that the greater articulatory possibilities of the high-front area of the oral cavity, in comparison to the back area, enable the expression of more differences among vowels (Crothers, 1978). The interpretation of the above data, however, should be examined more carefully in future research using comparable conditions such as number of participants and stimulus type.

Bark transformations

In order to try to characterize vowels produced by speakers of different gender and age, in such a way that variations among tokens of the same intended and perceived vowel are minimized and differences between perceptually distinct vowels are maximized, we adopted Syrdal and Gopal's (1986) model.

The transformation of physical frequency measures to an appropriate auditory scale is important for the understanding of the process of vowel recognition. The most appropriate scale for the representation of the complex speech spectrum is the critical (bark) scale. Zwicker (1961) proposed that the empirically defined critical band scale be adopted as a standard tonality scale. His proposed scale divides the human auditory range, below 16 kHz, into 24 critical units (barks).

In the present study transformations were performed on the acoustic data to model important aspects of the auditory processing of speech signals. This procedure included conversion of the frequency scale to the critical band scale and representation of each vowel as a pattern of differences between the frequency components. Classification of the resulting patterns was performed in each bark-difference dimension according to the criterion of a critical difference.

In the following section, the Syrdal and Gopal (1986) model will be applied on the acoustic data in an attempt to characterize the Hebrew vowels while minimizing group differences and normalizing the data. The mean measurements of F0, F1, F2, and F3 of each vowel by each group were transformed according to the formula suggested by Zwicker and Terhardt (1980) and according to the modification of Traunmüller (1981). Three bark-difference measures were calculated from the bark-transformed formant frequencies: F0 was subtracted from F1, F1 from F2, and F2 from F3. The bark-difference values define a three-dimensional auditory space in which each vowel is represented by a point. Table 4 presents the transformed F0, F1, F2, and F3 for the different vowels in the four groups, as well as the bark-difference values of the five vowels in the four groups.

A correspondence analysis was performed on the data presented in Table 4. According to this analysis similar relations were found among the five vowels and the bark-differences in the four groups. Thus, based on the transformed data as well as the untransformed data that was reported above, vowel differences were not group dependent.

According to Syrdal and Gopal (1986), the transformation of F0 and formant frequencies to the bark-difference dimensions constitutes an intermediate stage in auditory processing. The application of the 3-bark criterion to the bark-difference dimensions constitutes a higher phonetic stage of processing. According to this criterion, vowels are classified into two categories in each bark-difference dimension according to whether or

TABLE 4

Bark transformation mean values of the fundamental frequency (F0), the first three formants, and bark differences for three dimensions: F1-F0, F2-F1, and F3-F2 for the five Hebrew Vowels of the four groups

Vowel	*Group*	*F0*	*F1*	*F2*	*F3*	*F1-F0*	*F2-F1*	*F3-F2*
/i/	Men	1.48	3.31	13.32	14.66	*1.84*	10.01	*1.34*
	Women	2.09	3.67	14.64	15.54	*1.59*	10.97	*.90*
	Boys	2.66	3.89	15.25	16.30	*1.23*	11.36	*1.05*
	Girls	2.60	4.47	15.54	16.65	*1.87*	11.07	*1.11*
/e/	Men	1.48	4.34	11.89	14.52	*2.86*	7.55	*2.64*
	Women	1.95	5.15	13.71	15.43	3.20	8.57	*1.71*
	Boys	2.57	8.11	14.32	16.23	3.01	3.79	*1.91*
	Girls	2.51	5.86	14.54	16.37	3.35	4.09	*1.83*
/a/	Men	1.48	5.80	9.60	14.30	4.32	3.80	4.70
	Women	1.90	7.57	11.46	15.24	5.66	3.90	3.78
	Boys	2.57	8.11	11.90	15.98	5.54	3.79	4.08
	Girls	2.48	8.77	12.86	16.16	6.29	4.09	3.31
/o/	Men	1.48	4.54	8.15	14.32	3.07	3.60	6.17
	Women	1.98	5.10	8.43	15.39	3.12	3.34	6.95
	Boys	2.60	5.46	8.98	16.13	*2.86*	3.52	7.15
	Girls	2.53	6.04	10.03	16.34	3.51	3.99	6.32
/u/	Men	1.48	3.47	7.12	14.37	*1.99*	3.65	7.25
	Women	2.12	3.95	7.32	15.28	*1.82*	3.37	7.97
	Boys	2.69	3.97	7.46	16.08	*1.28*	3.49	8.62
	Girls	2.64	4.54	8.30	16.35	*1.90*	3.76	8.05

not they exceed a 3-bark critical difference. Following this reasoning, bark-differences less than the critical distance of three barks are italicized in Table 4.

Figure 3 presents the F1-F0 bark-difference as a function of F2-F1, and Figure 4 presents the F1-F0 dimension as a function of F3-F2 dimension.

Inspection of Table 4 and Figures 3 and 4 indicates several features of interest with respect to bark-difference dimensions for the five Hebrew vowels. The F1-F0 dimension corresponds well to the dimension of vowel height. High vowels (/i/, /u/) have F1-F0 values less than the critical distance of 3-barks for all groups. In all four groups, the F1-F0 values for the Hebrew low vowel (/a/) are greater than the critical distance. The mid vowels (/e/, /o/) are not distinctively classified in this dimension. The F1-F0 values for the vowel /e/ exceeded 3-bark for the women, girls, and for the boys' groups. Note, however, that the value for the boys' group was practically equal to three (3.01). For the men's group, the value on this dimension was within the critical distance. For the vowel /o/ the values on the F1-F0 dimension exceeded the critical distance for the women, girls, and for the men's groups. It was, however, within the critical distance for the boys' group. This analysis demonstrates and supports the articulatory-based division of the Hebrew vowels into three categories along the vowel-height dimension. Unlike the high vowels /i/ and

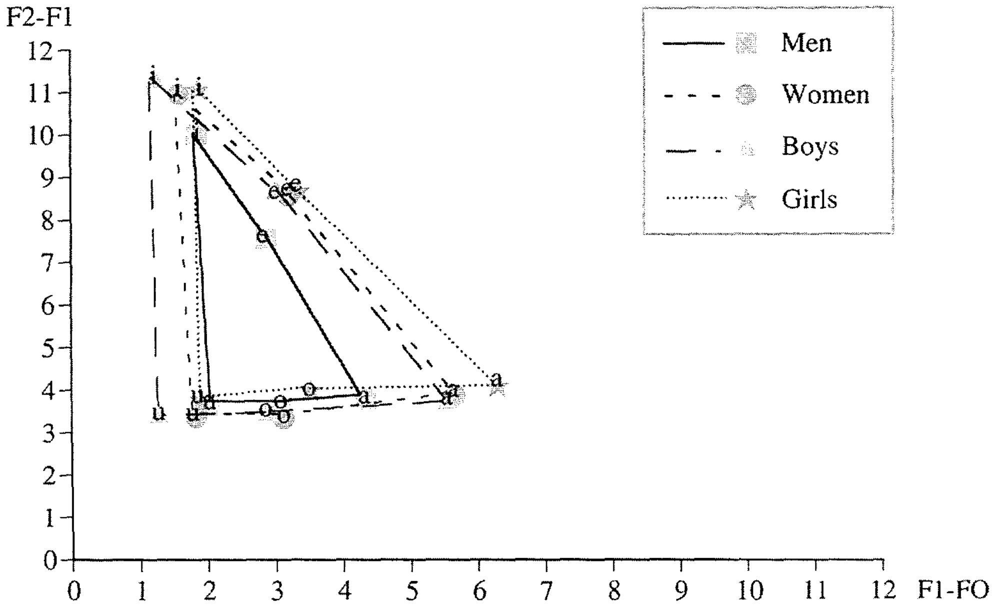

Figure 3: F1-F0 as a function of F2-F1 bark-difference dimension of the five Hebrew vowels produced by the four groups.

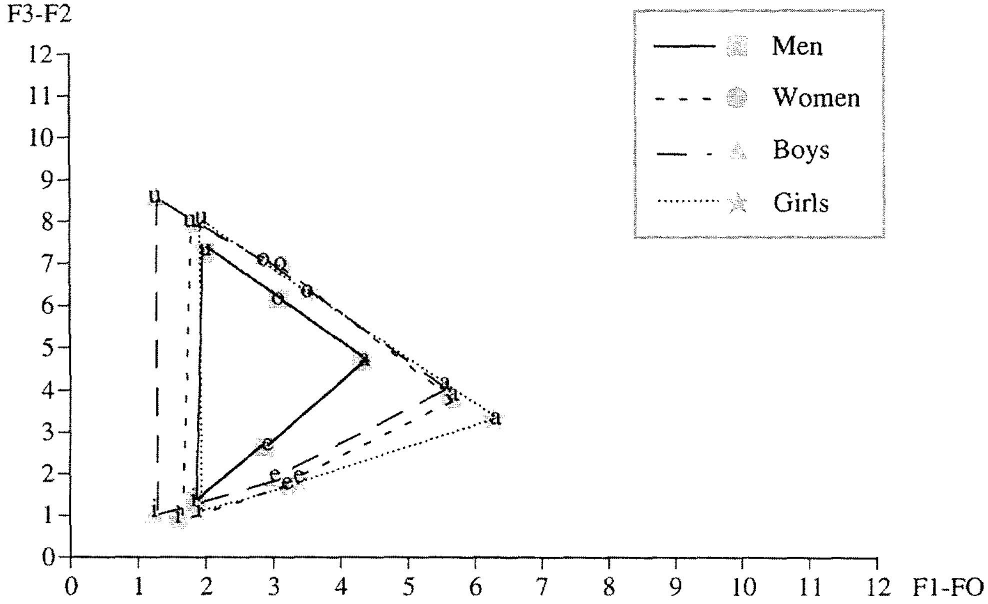

Figure 4: F1-F0 as a function of F3-F2 bark-difference dimension of the five Hebrew vowels produced by the four groups.

/u/ and the low vowel /a/; the vowels /e/ and /o/ are not distinctively classified in this dimension. Syrdal and Gopal (1986) also reported that the F1-F0 dimension was associated with the vowel height dimension for the ten American English vowels. According to their results high vowels /i, I, u, U/ have F1-F0 values less than the critical distance of 3-bark, whereas mid- and low-vowels predominantly have F1-F0 values greater than the critical distance. They concluded that the F1-F0 dimension represents a continuum of openness and provides a basis for binary classification. As mentioned above in Hebrew, three categories were observed on this dimension. It should be noted, though, that the most important difference between Hebrew and American English, in this respect, is the number of vowel phonemes. Therefore comparisons regarding phonological aspects of vowels should be based on a range of evidence, and not just on acoustic data. In Hebrew there are only five vowel phonemes, so the acoustic spaces are well separated (and hence more likely to be statistically different), whereas American English has more vowel phonemes, so the acoustic spaces overlap a lot more, and the difference between adjacent phonemes is less likely to reach statistical significance.

The F2-F1 values for all five vowels in all groups exceeded the 3-bark distance, ranging from 3.34 to 11.36. Thus, according to this analysis, Hebrew vowels are not separated into front and back categories along this dimension. Similar results were obtained for the American English vowels (Syrdal & Gopal, 1986). Unlike in the Swedish vowels where the F2-F1 dimension differentiated the front from the back vowels (Fant, 1983), in American English this dimension does not represent the continuum of vowel place of articulation. Thus the F2-F1 dimension cannot be said to relate universally to front-back vowel distinctions.

For Hebrew vowels, front and back vowels are clearly distinguished along the F3-F2 bark-difference dimension. As seen from Table 4 and Figure 4, the front vowels /i/ and /e/ have F3-F2 values less than 3-barks in all groups, and the back vowels (/a, o, u/) have F3-F2 differences which exceeded the critical differences. The Hebrew /a/ was previously defined as a central vowel (Laufer, 1983). However, this definition was based strictly on articulatory dimensions. The current analysis provides a quantitative perceptual evidence that the Hebrew /a/ should be classified as a back vowel. The F3-F2 dimension was reported previously to distinguish between front and back vowels in the American English vowels (Syrdal & Gopal, 1986). They too demonstrated that the five front vowels in English had F3-F2 values less than 3-bark, and back vowels had F3-F2 differences that exceeded the critical distance. It should be noted that, in general, the F3-F2 dimension was found to separate front from back vowels also in Swedish (Fant, 1983).

In summary, in Hebrew as in English, vowel height is defined through the F1-F0 dimension, and the vowel place is defined through the F3-F2 dimension. It appears that the vowel triangle in Figure 4 provides a more accurate perceptual representation of the relations between the acoustic and the phonetic features of the vowels. In the previous F2/F1 analysis we encountered an overlap between different vowels (/o/ and /u/) produced by different groups of speakers (men and girls). Inspection of Figure 4 in comparison to Figure 1 demonstrates that applying the bark scale as a speaker normalization procedure, indeed succeeded in reducing speaker differences while increasing vowel differences.

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