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## Effects of Aging on Vocal Fundamental Frequency and Vowel Formants in Men and Women

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### Abstract

**Purpose**—This study reports data on vocal fundamental frequency ( $f_0$ ) and the first four formant frequencies ( $F1$ ,  $F2$ ,  $F3$ ,  $F4$ ) for four vowels produced by speakers in 3 adult-age cohorts, in a test of the null hypothesis that there are no age-related changes in these variables. Participants were 43 men and 53 women between the ages of twenty to ninety-two years.

**Results**—The most consistent age-related effect was a decrease in  $f_0$  for women. Significant differences in  $F1$ ,  $F2$ , and  $F3$  were vowel-specific for both sexes. No significant differences were observed for the highest formant  $F4$ .

**Conclusions**—Women experience a significant decrease in  $f_0$ , which is likely related to menopause. Formant frequencies of the corner vowels change little across several decades of adult life, either because physiological aging has small effects on these variables or because individuals compensate for age-related changes in anatomy and physiology.

### Keywords

adult acoustics; aging voice; vowels; fundamental frequency; formants; sex differences

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## 1. Introduction

From infancy through young adulthood, the acoustic signal of speech undergoes substantial change, including marked decreases in both vocal fundamental frequency ( $f_0$ ) and the frequencies of the vowel formants [1]. These developmental changes are accompanied by a sexual dimorphism that is proportionately (i.e., male:female ratio) one of the largest in human development [2]. After adulthood, age-related changes in the acoustic properties of speech and voice are much less marked and conclusions across studies are inconsistent, with some studies showing no effects and others reporting a variety of effects such as a decrease of  $f_0$  in women [3, 4], an increase of  $f_0$  in men [3,4], a centralization of formant frequencies [5], a decrease in F1 frequency [6], decreases in all formant frequencies [7], and a sex-vowel interaction in formant frequencies [8].

Because results are not consistent across reports and because the aggregate number of individuals studied is small compared to the general population, it is difficult to draw firm conclusions on the effect of aging on speech acoustics. Even if acoustic changes occur with age, there are uncertainties in the interpretation of age- and sex-related variations. For example, changes in vowel formant frequencies during adulthood have been linked to lengthening of the vocal tract [7, 9], altered dimensions of the back cavity of the vocal tract [10], diachronic or intergenerational phonetic change [11, 12], reduction of articulatory movement [13], and adjustments of lingual articulation [14]. Possibly, two or more of these factors operate in combination to account for age-related acoustic changes in speech, and the combinations may vary among individuals.

Given the diverse results in previous studies, it is difficult at this time to describe a normative lifespan pattern for measures of  $f_0$  and formant frequencies in vowel production. A normative pattern is needed to inform studies of quality of life during aging [15], to serve as reference data for clinical assessment and treatment [16, 17, 18], to provide information for biometric identification and forensics [19] and speech technologies such as automatic speaker recognition [20]. Most of the relevant research to date has focused on  $f_0$  and other features of phonation. A much smaller literature has been published on the joint effects of aging on  $f_0$  and formant frequencies, and most of these reports present data only for F1 and F2, neglecting the higher formants, which may be sensitive to sex differences and alterations in vocal tract geometry.

More generally, little is known about the effects of aging on any aspect of speech production. Smiljanic [21] concluded that, “In contrast to the accumulated knowledge about the perceptual processing difficulties [in aging], very little is known about whether age-related changes impact speech production patterns for older adult talkers and the intelligibility of their speech” (p. EL129). Research to date, though limited, indicates that older adults have reduced speech intelligibility [22], greater impairment of phonological than semantic levels of language production [23], and difficulties with specific articulatory features [24]. Acoustic studies shed light on why intelligibility changes with age. For example, Benjamin [25] concluded that aging affected vowel productions, voice onset time, phoneme segment duration, and speaking rate. Schötz [26] reported age-related changes in speaking rate (segment duration), intensity range, and to a lesser extent,  $f_0$  and the

frequencies of the first two formants. She also noted that the acoustic correlates of aging speech are not the same in men and women. Because multiple acoustic cues underlie speech intelligibility, systematic research is needed to determine which cues, perhaps in various combinations, explain reduced intelligibility. Changes that occur in healthy aging are an important basis for understanding speech and voice disorders associated with health conditions that affect older individuals, such as hearing loss, Parkinson's disease, dementia, stroke, and cancer [27].

The purpose of this study is to test the null hypothesis that there are no age-related changes in  $f_0$  and the first four formant frequencies (F1, F2, F3, F4) for four vowels produced by speakers in 3 adult age cohorts. Several features of this research are notable. The test words used in this report are from a larger lifespan study of speech acoustics that covers the age range of 4 to 92 years. Constancy of the words across speakers throughout the lifespan facilitates comparisons and reduces variability related to the use of different speech samples across speaker ages. Collection of data for the first four formants, as opposed to just two formants, as has been the case in most studies, provides additional information that may be helpful in explaining age-related changes in formant pattern, for example, by referring to formant-cavity affiliations.

## 2. Methods

### 2.1 Participants

Speech recordings were from 96 healthy adult participants (43 male, 53 female), between the ages of 20 to 92 years. All participants met eligibility requirements as native English speakers. Ages were grouped into three cohorts, cohort I consisted of young adults (19 males, 21 females) ages 20 to 30 years, cohort II consisted of middle-aged adults (12 males, 20 females) ages 40 to 60 years, and cohort III consisted of older adults (12 males, 12 females) ages 70 to 92 years. No participant was excluded on the basis of hearing status. Not surprisingly, the majority of participants in cohort III had a hearing loss as determined by self-report or a screening test (9 wore hearing aids).

### 2.2. Speech sample

The speech stimuli consisted of 20 unique monosyllabic American English words. The words had the syllable structures of consonant-vowel, vowel-consonant, or consonant-vowel-consonant. The words were composed with the four corner vowels in the classic vowel quadrilateral: /i/ (bead, bee, eat, sheep, feet), /u/ (boo, boot, zoo, hoot, shoe), /æ/ (bath, bat, cat, hat, sad), and /ɑ/ (dot, hop, pot, top, hot). For each vowel, two of the stimuli were recorded twice (e.g., bead, eat, bat, hat). The stimuli were designed to collect data over the lifespan and were therefore chosen to be familiar to young children; also, to have high phonological neighborhood density, which reportedly maximizes F1/F2 acoustic vowel space [28].

### 2.3. Recording protocol

Participants were recorded in a quiet room in either a laboratory or a retirement center. Background noise levels were measured with a Fisher Scientific Sound Level Meter Model

11-661-6A with an A-weighting. The levels varied between 31 to 38 dBA, depending on the recording site. Recordings were made with a Shure-SM48 microphone mounted on a floor stand and attached to a Marantz digital recorder. The microphone was adjusted to each participant's seated height and positioned at an approximate 15 cm distance from the mouth. The Marantz-PMD660 digital audio recorder digitizes speech at 48 kHz with 16-bit resolution on a SanDisk Ultra II flashcard. To optimize recording level, the Marantz recorder gain was adjusted to 6 to 12 dB below the maximum level on the volume unit (VU) meter. Using a laptop with the TOCS+ Platform program [29] for randomization, the stimuli were presented visually and aurally using pictures with the orthographic word, while playing the recording of an adult male through external speakers. Participants were instructed to repeat the words at a normal loudness level. Two practice words were used at the beginning to adjust recording levels. During recording, stimuli that were mispronounced or considered to be deviant in VU meter reading were repeated and the repeated recording replaced the original productions.

#### 2.4. Acoustic analysis methods

Acoustic analysis were based on methods and criteria developed for the analysis of speech from speakers who represent various combinations of age and sex [30, 31]. The basic steps were as follows: Speech recordings were uploaded to a computer, segmented into separate word files with Praat (version 5.1.31 by Boersma & Weenink) [32], and saved into separate wave files. The vowel portion of each word was analyzed to obtain estimates of  $f_0$  and the first four formants (F1, F2, F3, F4) using the acoustic analysis software TF32, (Milenkovic 2010) [33]. The frequency of  $f_0$  was measured with the pitch determination algorithm in TF32. The formant frequencies were estimated with reference to the spectrogram (with overlaid formant tracks determined by LPC) and time-slice spectra from linear prediction coding (LPC) and Fast Fourier Transform (FFT). The LPC and FFT spectra were superimposed to permit comparisons. In cases where the LPC and FFT spectra were not congruent, reference was made to the spectrogram together with adjustments in analysis parameters, especially the number of LPC coefficients. The default setting for TF32 is a 300 Hz bandwidth and 48 dB dynamic range. Both the number of LPC coefficients and the dynamic range were adjusted to achieve optimum results for each speaker. Males were analyzed at 300 Hz, with a dynamic range adjusted between 48–64 dB. Females were analyzed at default settings, however, if formant energy was unclear, bandwidth was adjusted to 350 or 400 Hz and dynamic range could be adjusted as high as 68 dB. These procedures are consistent with general practice and recommendations for formant analysis using LPC and FFT [34, 35, 36, 37]. Because we have observed that the temporal midpoint of the vowel does not always correspond to a formant steady state, we used vowel-specific time points as defined by Derdemezis et al. [31] and similar to criteria used others [38]:

- a. Vowel /i/ -- point of highest F2 frequency;
- b. Vowel /u/ -- point of lowest F2 frequency;
- c. Vowel /a/ -- point of least separation of F1 and F2 frequencies;

- d. Vowel /æ/ -- point of most evenly spaced formants, taking care to avoid measurement at a point of decreasing F2-F1 difference which can reflect backing of the vowel.

The value of  $f_0$  was determined at the same time point as the formant measurements unless this time point occurred during an interval of vocal fry, pitch break, or other deviation from the overall  $f_0$  contour of the syllable. In such cases,  $f_0$  was measured at a proximal time point where the value was consistent with the contour of the utterance, as our interest was in the utterance-typical value of  $f_0$ .

## 2.5. Data analysis

Acoustic measurements for the cohorts I and II (young adult and middle-aged adults) were completed by 6 raters. One of these 6 raters made acoustic measurements for cohort III (older adults). All measurements for  $f_0$  and F1–F4 were visually examined for outliers, and unusual measurements were checked for possible data entry errors or other inconsistencies. There were no missing measurements for F1 and F2. However, some measurements could not be made for  $f_0$ , F3, and F4. The percentage of missing measurements were:  $f_0 < 1\%$  missing data, F3  $< 1.5\%$  missing data, and F4  $< 7\%$  missing data. Since an important goal for this database is to provide normative data for adult age cohorts, outliers that exceeded 2.576 SD from their Age cohort x Sex mean were excluded from this analysis. This ensured that there was a low probability (1%) of excluding data incorrectly, but also guarded against large outliers having undue influence on the age cohort analysis. Outliers removed were less than 1.8% of the total data. To assess reliability, raters' inter- and intra-rater reliability was measured using the *intraclass correlation coefficient* (ICC), which can be thought of as the correlation of observations within a subject (with the value 1 being the maximal possible reproducibility of the frequency measurements). Inter-rater reliability was assessed using a two-way random effects model, with the assumption that the raters came from a larger population of possible raters. A random subset of recordings from six participants were measured by all raters. Reliability among the raters was excellent, with ICC values  $> .96$  for all vowels/formants except F1 of /æ/ where ICC was .69 but still considered good reliability. To assess intra-rater reliability for Cohort III, a random sample of six older adults was re-measured by the same rater. Again, reliability was excellent with ICC  $> .91$  for all vowels and formants with the exception of F4 for /i/ where ICC was .714 but still considered very good reliability.

## 2.6. Statistical methods

All analyses were completed using the Statistical Analysis System (SAS) software (version 9.4 by SAS Institute, Inc., 2013). Mixed effects models were used to compare fundamental frequency and the first four formants across age cohorts. Fixed effects included Sex, Age/cohort, and Sex X Age cohort interaction. A random effect for subject was included in the mixed models to account for the correlation of repeat words from the same subject. Comparisons of interest for males and females were between the following three age cohorts in years: Cohort I (ages 20–30) vs. cohort II (ages 40–60), cohort II vs. cohort III (ages 70–92), and cohort I vs. cohort III. The Bonferroni method was used to adjust p-values to

account for multiple comparisons for each model, with a p-value of  $.05/6 = .0083$  indicating significant differences.

### 3. Results

Findings revealed the expected significant differences by sex for all vowels and all frequencies,  $f_0$  and all formants, see Table 1. Age cohort differences are displayed in Figures 1 and 2 as well as Tables 1 and 2. Findings revealed significant differences among age cohorts for all vowels for  $f_0$ , and for /i/, /u/ and /æ/ for F1 and F2. There was a significant Age cohort X Sex interaction for all vowels for  $f_0$ , for /u/ and /æ/ for F1, and for /æ/ for F3, indicating that the differences among age cohorts varied by sex. Given the interaction, the boxplots in Figures 1 and 2 display the findings separately by speaker sex to display age group/cohort differences more clearly. Table 2 shows the model means (least squares means) for each frequency ( $f_0$ , F1, F2, F3, F4) by vowel for each sex and age cohort, and indicates significant age cohort differences.

As seen in Figure 1 and Table 2, the young adult women in age cohort I had significantly higher  $f_0$  than middle-aged women in cohort II for all vowels. Differences (cohort I–cohort II) in least square means by vowel were: /i/ 35 Hz,  $p < .0001$ ; /u/ 34 Hz,  $p < .0001$ ; /æ/ 38 Hz,  $p < .0001$ ; /ɑ/ 35 Hz,  $p < .0001$ . As seen in Figure 2 and Table 2, women in cohort I had significantly higher F1 than cohort II for /i/ (34 Hz,  $p = .0005$ ), /u/ (51 Hz,  $p < .0001$ ), and /æ/ (82 Hz,  $p = .0006$ ); significantly higher F2 for /u/ (110 Hz,  $p = .0014$ ) but significantly lower F2 for /æ/ (–133 Hz,  $p = .0032$ ). The comparison of young adult women in age cohort I to older adult women in cohort III also revealed younger women to have significantly higher  $f_0$  for all vowels (/i/ 23 Hz,  $p = .0031$ ; /u/ 24 Hz,  $p = .0019$ ; /æ/ 39 Hz,  $p < .0001$ ; /ɑ/ 30 Hz,  $p < .0001$ ), higher F1 for /u/ (49 Hz,  $p < .0001$ ) and /æ/ (131 Hz,  $p < .0001$ ), and higher F2 for /u/ (151 Hz,  $p = .0002$ ). There were no significant differences between middle-aged women (cohort II) and older women (cohort III) for  $f_0$ , F1, or F2. In addition, there were no significant differences for F3 and F4 between any of the age cohorts indicating stability of these formant frequencies across age in women.

For men, there were only two significant differences in vowel frequencies between age cohorts. As seen in Figure 2 and Table 2, young adult men (cohort I) had significantly higher F2 than older adult men (cohort III) for /u/ (138 Hz,  $p = .0007$ ) and significantly higher F3 for /æ/ (162 Hz,  $p = .0033$ ). There were no significant differences between any of the age cohort comparisons for men for  $f_0$ , F1, or F4.

Figure 3 displays a comparison of the current F1–F2 data with those of two frequently cited studies of vowel formants, Peterson and Barney (1952) [39] and Hillenbrand, Getty, Clark, and Wheeler (1995) [34]. The current results for men in all age cohorts are nearly congruent with those of Peterson and Barney [39]. The current data for women agree with those of Peterson and Barney [39] for the high vowels but differ somewhat for the low vowels. For both men and women in the present study, there is no indication of centralization or lowering of formant frequencies in the vowel quadrilaterals for any of the age cohorts.

## 4. Discussion

The results of the present study and previously published studies on vowel formants are compiled in Table 3 which provides an overall view of age-related changes in vowel acoustics. This summary table provides an overview of research and is helpful to determine the extent of agreement across studies. There does not appear to be an invariant pattern of age-related changes. But it should be noted that the aggregate number of research participants in Table 3 is no more than a few hundred, which is hardly sufficient to generalize to the aging population at large. Approximately 42 million people in the U.S.A. were age 65 or older in 2012 [40] and by all projections, the number is increasing as longevity increases. It is almost certainly the case that changes would be observed in some individuals or some groups selected according to criteria such as health status. In this connection, it should be noted that many participants in the published studies probably were self-selected to be relatively healthy, on the assumption that healthy and vigorous individuals are more likely than their less healthy counterparts to volunteer for research studies. Research on a much larger sample is needed to establish the nature of formant changes with aging. Until such an ambitious project is undertaken, the current wisdom is necessarily based on the combination of longitudinal and cross-sectional studies summarized in Table 3. What is clear from this table is that vowel formants do not systematically decrease with age and may not decrease at all in some individuals. Variable results are not surprising given that the studies summarized in Table 3 used different methods (including speech sample, recording equipment, and analysis procedure) and had different criteria for participant selection.

The studies listed in Table 3 are those that report vowel formant values with or without data on  $f_0$ . A much larger literature has accumulated specifically on  $f_0$  [41, 42]. Although the studies are not in complete agreement, a general conclusion from the preponderance of the data is that  $f_0$  decreases with age in both men and women, with the larger change occurring in women. The present results point to a significant age-related decrease in  $f_0$  in women. In contrast, the men had a trend of slight increases in  $f_0$  between each of the age cohorts but the changes were not statistically significant. Previous studies reporting increased  $f_0$  in men include: Cox and Selent, (2015)[43], Nishio and Niimi (2008)[44], along with three studies cited in Table 3. Previous studies reporting decreased  $f_0$  in women include Nishio and Niimi (2008) [44] and several studies cited in Table 3. The results reported for formants are quite variable and the most consistent finding is a reduced F1 frequency, especially in women. The explanation for this finding is uncertain and may be related to articulatory variations rather than aging of the vocal tract tissues. As shown in Figure 3, the women in the present study produced vowels with highly distinctive F1–F2 patterns.

The present study extends previous research by reporting data for the first four formants of the quadrilateral vowels in American English. It was expected that the data for four formants would help to determine the presence of general processes such as vowel tract lengthening (which should result in decreases of all formant frequencies) or centralization (which should result in movement to the centroid of formant space). For both men and women, the frequencies of F3 and F4 were essentially unchanged across the age cohorts. This result agrees with that of Schötz [26], one of the few studies that analyzed higher formants and is

notable for the relatively large number of research participants. The lack of an aging effect on the higher formants supports the idea that any changes found for F1 and F2 are related to specific articulatory effects rather than generalized processes such as lengthening of the vocal tract. It is notable that formant frequencies were unaffected in the oldest cohort even though the majority of participants in this group had a hearing loss.

Conclusions on the effects of aging on speech should be drawn with great caution. With this caveat in mind, we offer tentative conclusions as follows: Vowel formant frequencies change little if at all across several decades of adult life, either because physiological aging has small effects on these variables or because individuals compensate for age-related changes in anatomy and physiology. Changes in formant frequencies do not seem to be inevitable with aging. A clinical implication is that normative acoustic data on vowel production by adults do not require substantial age adjustments. A related implication is that if substantial changes are observed in an aging individual, they may indicate pathology but not necessarily so. Regarding  $f_0$ , studies generally point to a decrease in both sexes, but especially women. The  $f_0$  changes in women may be related to a number of age-related physiologic changes, including hormonal changes after menopause [45, 46]; decrease in size of the laryngeal muscles, hardening and possible ossification of the laryngeal cartilages [47]; decreased glandular function [49]; and edema, bowing, and/or thickening of the vocal folds [48; 9]. Given that only women showed a significant effect of aging in this study, particularly between cohort I and II and not between cohort II and III, it is likely that hormonal changes explain the decreased  $f_0$  in women. This explanation is based on the safe assumption that all women in Cohort III were postmenopausal since by age 58 years, 100% of women have reached menopause [50].

A normative standard for vowel formants and derived indices such as vowel space area is important clinically given their use in assessing speech functions and monitoring treatment for various disorders that often are age-related, including acquired dysarthria [51, 52, 53, 54], glossectomy [55, 56], oral or oropharyngeal cancer [57], and individuals in psychological distress or with self-reported symptoms of depression and post-traumatic stress disorder [58, 59].

The present study adds to the gradually accumulating body of data on the effects of aging on the acoustic properties of speech. Progress would be aided considerably by conduct of a much larger study involving hundreds of participants of both sexes participating in a carefully selected set of speech and voice tasks. Ideally, participants would be described by health-related variables to account for differences in health states. This is particularly important given evidence that physiological differences among individuals may become greater with advancing age [60]. A possible outcome of such a study is that the data would indicate the presence of subgroups of individuals who have different patterns of aging effects. Until such a large-scale study is undertaken, the results summarized in Table 3 caution against any sweeping conclusions on the effects of aging on vowel formants.

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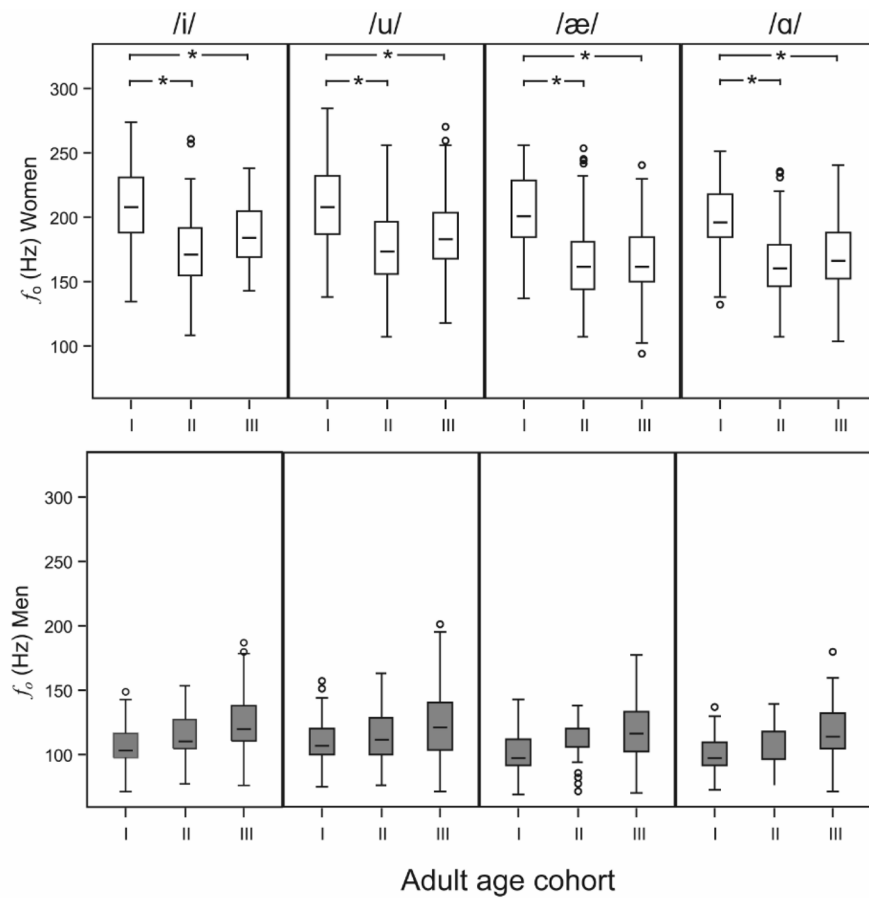
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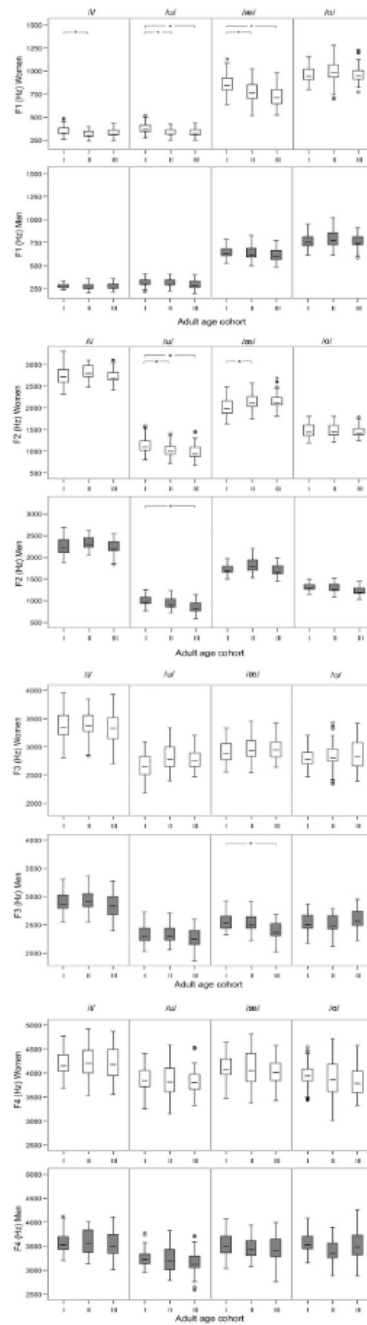
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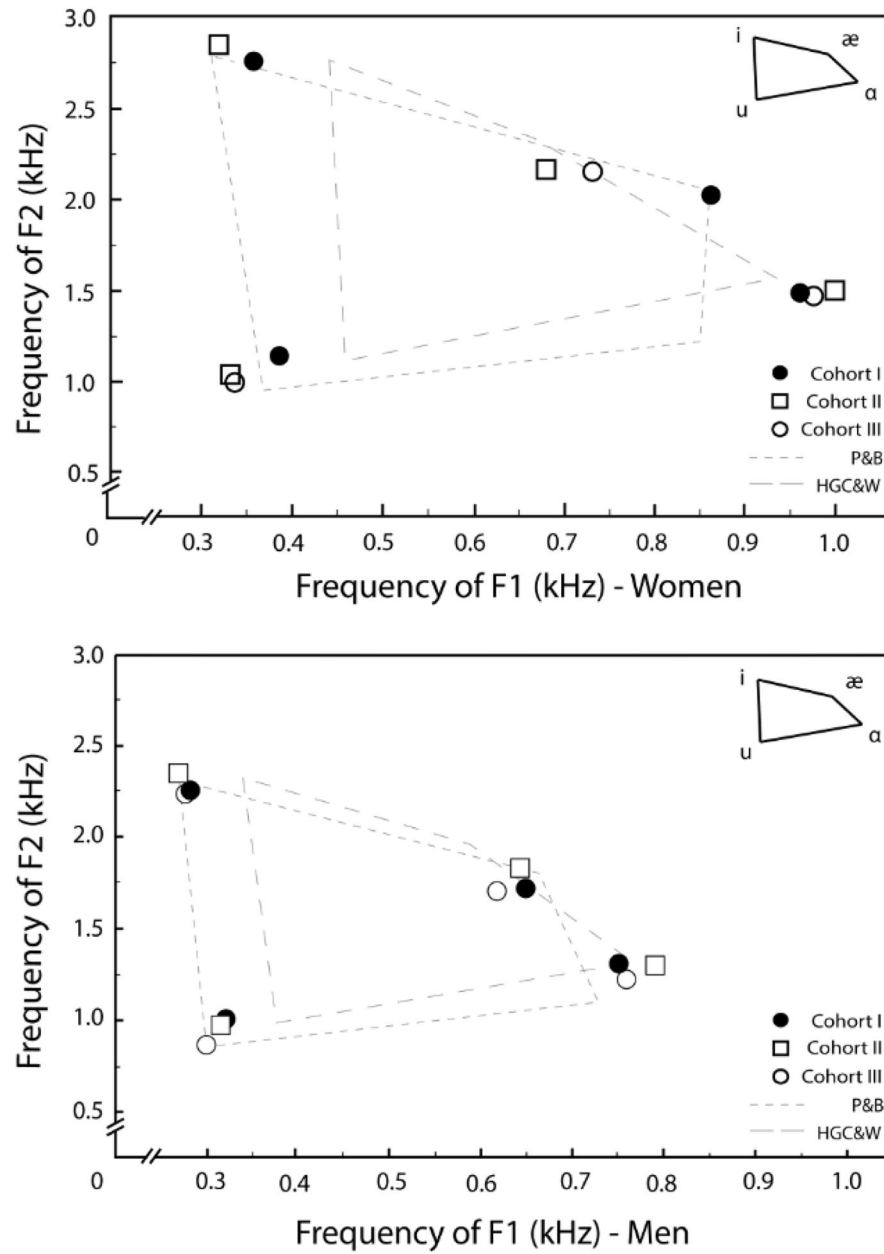
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**Figure 1.** Vowel-specific fundamental frequency ( $f_0$ ) for cohort I (young adults), cohort II (middle-aged adults) and cohort III (older adults). Top panel shows the box and whisker plots for women and bottom panel for men. The boxplots show the 25<sup>th</sup> and 75<sup>th</sup> percentiles and the dash line represents the mean. The whiskers show the maximum and minimum values excluding outliers. Outlying data (greater than 1.5 times the intra-quartile range above or below the box) are shown as open round symbols. Asterisk denotes significant age cohort differences.



**Figure 2.** Vowel-specific frequencies (first through fourth formants) for cohort I (young adults), cohort II (middle-aged adults) and cohort III (older adults). Top panel shows the box and whisker plots for women and bottom panel for men. See Figure 1 caption for boxplot information. Asterisk denotes significant age cohort differences.



**Figure 3.**

Average F1–F2 data for each of the three age cohorts superimposed on the F1–F2 acoustic space from Peterson and Barney (1952; P&B)[39] and Hillenbrand et al. (1995; HGC&W) [34]. Top figure shows the data for women and bottom figure for men.

Table 1

Results of mixed models estimating the effect of sex, age cohort and sex X age cohort interaction on vowel fundamental frequencies and formants.

Measure	Vowel	Sex		Age cohort		Sex X Age cohort	
		F (1,90)	p-value	F (2,90)	p-value	F (2,90)	p-value
$f_0$	i	289.37	<.0001 *	3.96	0.0225 *	10.84	<.0001 *
	u	288.44	<.0001 *	4.49	0.0138 *	9.41	0.0002 *
	æ	242.91	<.0001 *	5.04	0.0084 *	17.55	<.0001 *
F1	ɑ	274.11	<.0001 *	4.51	0.0136 *	14.61	<.0001 *
	i	87.75	<.0001 *	4.53	0.0134 *	1.63	0.2010
	u	41.77	<.0001 *	10.85	<.0001 *	5.72	0.0046 *
F2	æ	100.10	<.0001 *	9.35	0.0002 *	4.05	0.0207 *
	ɑ	133.96	<.0001 *	1.11	0.3342	0.07	0.9323
	i	219.36	<.0001 *	3.26	0.0430 *	0.01	0.9924
F3	u	27.43	<.0001 *	14.48	<.0001 *	0.50	0.6105
	æ	155.69	<.0001 *	6.07	0.0034 *	2.31	0.1051
	ɑ	96.72	<.0001 *	2.78	0.0672	0.91	0.4052
F4	i	154.43	<.0001 *	0.97	0.3839	0.09	0.9147
	u	165.84	<.0001 *	1.54	0.2205	2.29	0.1069
	æ	216.52	<.0001 *	1.26	0.2873	4.25	0.0172 *
F4	ɑ	67.07	<.0001 *	1.14	0.3240	0.22	0.8009
	i	156.51	<.0001 *	0.24	0.7842	0.02	0.9849
	u	169.92	<.0001 *	0.79	0.4558	0.12	0.8837
F4	æ	139.79	<.0001 *	1.11	0.3336	0.20	0.8155
	ɑ	57.17	<.0001 *	2.23	0.1139	1.35	0.2638

\* Fixed effect is significant at  $p < .05$  alpha level.

**Table 2**

Least squares means from mixed models for three adult age cohorts for women and men, with indicators for significant differences.

	Female				Male			
	20-30	40-60	70+		20-30	40-60	70+	
	Mean (SE)	Mean (SE)	Mean (SE)		Mean (SE)	Mean (SE)	Mean (SE)	
<i>f</i> <sub>6</sub>	i 212 (4.65) 1,2	177 (4.78) 1	188 (6.16) 2		108 (4.90)	115 (6.15)	125 (6.16)	
	u 211 (4.54) 1,2	178 (4.66) 1	187 (6.01) 2		112 (4.79)	115 (6.00)	126 (6.02)	
	æ 205 (4.54) 1,2	167 (4.66) 1	166 (6.01) 2		103 (4.78)	110 (6.00)	120 (6.01)	
	ɑ 200 (4.31) 1,2	165 (4.42) 1	170 (5.71) 2		102 (4.55)	108 (5.70)	119 (5.71)	
F1	i 355 (6.54) 1	322 (6.69) 1	332 (8.64)		282 (6.86)	274 (8.63)	276 (8.63)	
	u 386 (6.76) 1,2	335 (6.92) 1	337 (8.92) 2		317 (7.09)	316 (8.92)	299 (8.92)	
	æ 865 (16.16) 1,2	783 (16.56) 1	734 (21.39) 2		650 (16.99)	645 (21.44)	618 (21.41)	
	ɑ 965 (18.17)	998 (18.62)	974 (24.04)		770 (19.10)	793 (24.02)	764 (24.04)	
F2	i 2761 (35.37)	2838 (36.25)	2732 (46.79)		2250 (37.18)	2332 (46.79)	2230 (46.80)	
	u 1145 (23.36) 1,2	1035 (23.96) 1	994 (30.95) 2		1006 (24.55) 2	946 (30.90)	867 (30.90) 2	
	æ 2027 (30.51) 1	2159 (31.27) 1	2163 (40.39)		1720 (32.08)	1822 (40.37)	1704 (40.37)	
	ɑ 1488 (21.26)	1496 (21.78)	1466 (28.13)		1317 (22.36)	1300 (28.12)	1227 (28.13)	
F3	i 3376 (39.53)	3403 (40.54)	3354 (52.27)		2908 (41.51)	2944 (52.30)	2855 (52.42)	
	u 2682 (35.34)	2814 (36.22)	2783 (46.74)		2338 (37.17)	2343 (46.74)	2278 (46.74)	
	æ 2918 (31.71)	2964 (32.53)	2976 (42.03)		2567 (33.32) 2	2533 (41.94)	2406 (41.93) 2	
	ɑ 2815 (35.84)	2838 (36.72)	2867 (47.44)		2539 (37.66)	2521 (47.42)	2607 (47.52)	
F4	i 4195 (51.82)	4228 (54.54)	4191 (69.94)		3573 (54.49)	3598 (68.60)	3547 (68.63)	
	u 3883 (50.17)	3855 (51.44)	3838 (66.42)		3273 (52.90)	3235 (66.39)	3170 (66.39)	
	æ 4118 (53.11)	4123 (56.46)	4051 (70.45)		3549 (55.88)	3482 (70.42)	3430 (70.30)	
	ɑ 3975 (53.73)	3901 (55.16)	3819 (71.17)		3567 (56.50)	3403 (71.08)	3543 (71.68)	

<sup>1</sup> Significant difference ( $p < .0083$ ) between ages 20-30 vs. 40-60.

<sup>2</sup> Significant difference ( $p < .0083$ ) between ages 20-30 vs. 70+.



**Table 3**Summary of studies of effects of aging on vowel formants (and  $f_0$  when included in the study).

Source	Participants	Change in $f_0$	Change in F1	Change in F2
Cox & Selent (2015) [43]	35 men in five age cohorts	Decreased	NA	NA
Debruyne & Decoster (1999) [61]	40 young adults (20 male, 20 female) and 40 older adults (20 male, 20 female)	Increased in men, decreased in women	Decreased in men and women	Decreased in men and women
Endres, Bambach, & Flosser (1971) [7]	Longitudinal study of 2 men and 3 women over a time span of 13 to 15 years	Decreased in men and women	Decreased in men and women	Decreased in men and women
Linville & Fisher (1985) [14]	75 women at three age levels (25 to 35, 45 to 55, 70 to 80)	NA	Decreased in women for one vowel studied	--
Fletcher, McAuliffe, Lansford, & Liss (2015) [62]	149 speakers of New Zealand English (55 males, 94 females), aged between 65 and 90	NA	No change	No change
Harrington, Palethorpe, & Watson (2007) [6]	Longitudinal study of 2 men and 2 women over varying spans of time	Decreased in both men and women	Decreased in both men and women	--
Kaur & Narang (2015) [63]	Unspecified number of women in two age groups	Decreased in women	Decreased in women	Decreased in women
Linville & Rens (2001) [9]		NA	Decreased in both men and women	Decreased in women; tended to decrease in men
Mwangi et al. (2009) [64]	One speaker (Queen Elizabeth II) from age 26 to 76 years	Decreased	Decreased	No change
Rastatter & Jaques (1990) [5]	20 young adults (10 men, 10 women; mean age of 21) 20 older adults (10 men, 10 women, mean age of 74)	NA	Varied with vowel for both men and women; apparent centralization	Varied with vowel for both men and women; apparent centralization
Reubold, Harrington, & Kleber (2010) [65]	Longitudinal study of 2 men and 3 women over a time span of at least XX years	Decreased in women but one man showed a decrease followed by an increase in old age	Decreased for schwa vowel	No consistent change
Scukanec & Petrosino (1991) [10]	6 young women (mean age of 21) and 3 older women (mean age of 68)	NA	Decreased for 4 vowels studied in women	Decreased for back vowels in women
Schötz (2006) [26]	269 women and 268 men ranging age from 18 to 90 years	In women, decreased until age 50, followed by a slight increase until age group 70, then another decrease; in men, slight decrease until age 50, followed by an increase into old age	F1 decreased in some vowels	No consistent change
Sebastian, Babu, Oommen & Ballraj (2012) [66]	20 men (age range of 60–80) and 20 women (age ranges of 60–80) were divided into 4 age groups (60–64, 65–69, 70–74, and 75–79) with 5 subjects in each group.	Increased in men, decreased in women	No change	No change
Torre & Barlow (2009) [3]	27 young adults (12 men and 15 women, mean age of 25.5) and 59 older adults (27	Increased in men, decreased in women	Decreased for some vowels for men, decreased for all vowels in women	Interacted with sex and vowel

Source	Participants	Change in $f_0$	Change in F1	Change in F2
	men and 32 women, mean age of 75)			
Vorperian et al. (present study)	43 men and 53 women between the ages of 20 and 92 years	Decreased in women	Varied with vowel	Varied with vowel
Xue, Jiang, Lin, Glassenberg, & Mueller (1999) [8]	10 young women (mean age of 40) and 12 older women (mean age of 56)	NA	Decreased in men and women	Varied with vowel
Xue & Hao (2003) [67]	38 young adults (19 men and 19 women, mean age of 22) and 38 older adults (19 men and 19 women, mean ages of 71 and 74, respectively)	NA	Decreased for most vowels in men and women	Decreased depending on vowel in men and women