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Sex-specific fundamental and formant frequency patterns in a cross-sectional study

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Abstract

An extensive developmental acoustic study of the speech patterns of children and adults was reported by Lee and colleagues [Lee et al., J. Acoust. Soc. Am. 105, 1455-1468 (1999)]. This paper presents a reexamination of selected fundamental frequency and formant frequency data presented in their report for 10 monophthongs by investigating sex-specific and developmental patterns using two different approaches. The first of these includes the investigation of age- and sex-specific formant frequency patterns in the monophthongs. The second, the investigation of fundamental frequency and formant frequency data using the critical band rate (bark) scale and a number of acoustic-phonetic dimensions of the monophthongs from an age- and sex-specific perspective. These acoustic-phonetic dimensions include: vowel spaces and distances from speaker centroids; frequency differences between the formant frequencies of males and females; vowel openness/closeness and frontness/backness; the degree of vocal effort; and formant frequency ranges. Both approaches reveal both age- and sex-specific development patterns which also appear to be dependent on whether vowels are peripheral or non-peripheral. The developmental emergence of these sex-specific differences are discussed with reference to anatomical, physiological, sociophonetic and culturally determined factors. Some directions for further investigation into the age-linked sex differences in speech across the lifespan are also proposed.

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INTRODUCTION

Sex differences in the formant frequency values of adults are well established and widely documented (e.g. Childers and Wu, 1991; Deterding, 1997; Peterson and Barney, 1952; Wu and Childers, 1991). In addition, the non-uniform patterns of sex differences across different formant frequencies and vowels are well-established and have been observed across different languages (Fant, 1975; Traunmüller, 1984, 1988). These non-uniform sex differences highlight the non-linear sex differences in the vocal tract dimensions of men and women (Fant, 1966, 1975; Fitch and Giedd, 1999) and explain the developmental emergence of non-linear sex differences in the formant frequency data of preadolescent children (e.g. Bennett, 1981; Busby and Plant, 1995; Eguchi and Hirsh, 1969; White, 1999; Whiteside and Hodgson, 2000).

There is some acoustic-phonetic evidence which suggests that women have more peripheral vowel spaces compared to men (e.g. Deterding, 1997; Henton, 1995; Traunmüller, 1988), and this seems to hold true across a number of different languages including General American English, Italian, Japanese, British English (Middle Northern), German, Swedish, Standard Dutch and French (e.g. see Henton (1995) and Rosner and Pickering (1994) for details and summaries of these data). The more peripheral nature of vowel spaces exhibited by women has been attributed to sociophonetic factors which determine the different speech styles adopted by men and women (Henton, 1995). However, an alternative view is that the emergence of sex differences in the acoustic-phonetic characteristics of vowels can be explained by physiological factors and anatomical constraints, which are due to maturational differences between males and females (Traunmüller, 1984, 1988).

A recent and extensive contribution to the developmental literature on speech characteristics comes from Lee and colleagues (Lee *et al.*, 1999), who report on speech data collected from 436 children aged 5 to 18 years, and 56 adults (aged 25-50 years). Their study includes data on fundamental frequency and formant frequency data from 10 monophthongs of American English. In their presentation and discussion of their data, the authors mention the need for a more detailed and thorough investigation of their data.

This paper aims to re-examine and elaborate on some of the fundamental and formant frequency data presented by Lee *et al*. (1999) by adopting a sex-specific developmental perspective, and exploring some of the factors that may be responsible for age-linked sex differences in these acoustic-phonetic parameters. The fundamental frequency and formant frequency data presented by Lee *et al.* (1999) are re-examined using a number of approaches. The first of these involves the application of kn-factors (Fant, 1966, 1975), and the second, the investigation of vowel spaces and acoustic-phonetic parameters using the critical band rate (bark) scale (Traunmüller, 1988, 1990). Both approaches adopt an age- and sex-specific perspective.

In order to investigate within-sex patterns as a function of development, *kn-age* factors are derived for each of the male and female formant frequency data following Fant (1966, 1975). The motivation here is to chart and gauge the developmental patterns of formant frequencies of males and females separately, as a function of chronological age. Further, to investigate the emergence of sex differences across the lifespan, *kn-sex* factors are examined by gauging the male-female differences in formant frequencies across all vowels and selected vowels for the different age groups. The findings of this reanalysis of the formant frequency data reported by Lee *et al.*, (1999) are presented and discussed with reference to developmental patterns previously reported for formant frequencies (e.g. Bennett, 1981; Busby and Plant, 1995; Eguchi and Hirsh, 1969; White, 1999), and developmental patterns in the morphology of the human vocal tract (e.g. Fitch and Giedd, 1999).

The formant frequency data reported by Lee *et al.* (1999) are also investigated using an approach which determines the distances of formant frequency values from speaker centroids as a measure of vowel space (e.g. Deterding, 1997). Acoustic-phonetic parameters expressed in the critical band rate (bark) scale have been shown to be effective in highlighting the ontogeny of sex-specific variation in the vowel quality of peripheral vowels (Traunmüller, 1988). Given that the 10 monophthongal vowels reported by Lee *et al.* (1999) included both peripheral and non-peripheral vowels, the acoustic-phonetic quality of peripheral and non-peripheral vowels is examined separately using a number of acoustic-phonetic parameters based on the critical band rate (bark) scale from a sex-specific and developmental perspective. The patterns that emerge from this re-examination are discussed with reference to the sex-linked developmental trends in the data, and whether they shed any light on any factors that may be responsible for influencing the emergence of speaker sex differences in the phonetic quality of vowels (e.g. Henton, 1995; Rosner and Pickering, 1994; Traunmüller, 1988).

I. METHODS

A. Kn-age and kn-sex factors

The mean formant frequency values (F1 to F3) for the monophthongs of all age groups from age 7[1] years to those of the adults, reported by Lee *et al.* (1999) were examined for vowel-specific patterns, and related sex-specific and developmental changes. The 10 monophthongs reported by Lee *et al.* (1999, p. 1456) are as follows: aa (*pot*); ae (*bat*); ah (*but*); ao (*ball*); eh (*bet*); er (*bird*); ih (*bit*); iy (*bead*); uh (*put*); uw (*boot*).[2]

Following Fant (1966, 1975) scaling factors were calculated for each of the formant frequency values (F1, F2, F3), and across all three formant frequencies ((F1+F2+F3)/3) to examine both within-sex-age-linked developmental patterns, and sex-specific developmental changes. Within-sex-age-linked developmental patterns were examined by applying the formula (1) to give two sets of *kn-age* values for the male and female speakers. These *kn-age* values allowed the examination of developmental changes in formant frequency values for each sex group, with reference to the adult formant frequency values. In addition, within-age sex-linked developmental patterns for formant frequency values were examined by using formula (2) to give one set of *kn-sex* factors. These *kn-sex* factors allowed the tracking of developmental patterns in within-age sex differences with increasing chronological age. Both kn-age and kn-sex factors were examined in more detail for a selected group of vowels which represented a range of acoustic-phonetic vowel quality dimensions of openness, constriction, rhoticity, frontness and backness. These selected vowels were aa, ah, er, ih, iy and uw.

Kn = Fn/ Ref Fn

Fn: Female or Male formant frequency value

Ref Fn: Formant frequency value of adult female (in the case of female Fn value) or adult male (in the case of male Fn value) formant frequency value. For example, the mean adult male value of F1 (Vowel aa, 723 Hz) serves as the reference value for the corresponding F1 value for the male 18 year olds (Vowel aa, 737 Hz), to derive a k1 age factor value of 1.02 for the male 18 year olds. (1)

Kn = Fn/ Ref Fn

Fn: Female formant frequency value

Ref Fn: Formant frequency value of Male age peer formant frequency value. For example, the male value of F1 (Vowel aa, 723 Hz) for the 18 year-old group serves as the reference value for the corresponding F1 value for the female 18 year old group (Vowel aa, 894 Hz). This therefore gives a k1 sex factor of 1.26 for the 18 year-olds. (2)

B. Conversion of fundamental frequency and formant frequency values from hertz to Bark to examine vowel spaces and critical band rate (bark) distances

The aim here was to investigate sex-linked developmental patterns in the vowel spaces of the male and female speakers of each age group. This re-examination was carried out as follows. Firstly, the fundamental frequency (F0) and formant frequency data (in hertz) for the 10 vowels reported by Lee *et al.* (1999) were converted to the Bark auditory scale, using the formula described by Traunmüller (1988, 1990). This formula for the Bark scale is an alternative to that documented by Zwicker and Terhadt (1980) where Z is the frequency in the Bark scale and F is the frequency in hertz as given in formula (3). In addition, all fundamental frequency values less than 2.0 Bark were corrected using formula (4) (Traunmüller, 1990).

$$Z=[26.81F/(1960+F)]-0.53 \quad (3)$$

$$\text{For calculated } Z<2.0 \text{ Bark: } Z'=Z+0.15(2-Z) \quad (4)$$

Subsequently, vowel spaces of the 13 age groups were determined for the males and females of each age group using the critical band rate (bark) values. This was done by plotting the difference between F1 and F0 (F1-F0) as a speaker-independent index of degree of openness (Traunmüller, 1981), against the difference between F2 and F1 (F2-F1), as a general index of anterior/posterior position of constriction (Ladefoged and Maddieson, 1990). This method was used to normalize for sex differences, and was therefore chosen to highlight any developmental sex differences within the defined F1-F0/F2-F1 vowel space of the 10 vowels after normalization.

In order to determine tonotopic distances between vowels in the vowel space defined by F2-F1/F1-F0, the speaker centroids of the vowel space for the male and female speakers were calculated separately for each age and sex group from the mean F1-F0 and F2-F1 values of all 10 vowels formula (5). In (5) *D* refers to the distance of vowel V from the speaker centroid of each age and sex group vowel space, *xcentroid* to the F2-F1 co-ordinate of the speaker centroid, *ycentroid* to the F1-F0 co-ordinate of the speaker centroid, *x-V* to the F2-F1 value for vowel V, and *y-V* to the F1-F0 value for vowel V. The application of formula (5) gleaned a total of 26 sets of speaker centroid values and vowel distances (2 (males and females) x 13 (age groups)).

$$D= \text{SQRT}\ ((xV - xcentroid)^{\wedge 2} + (yV - ycentroid)^{\wedge 2}). \quad (5)$$

C. Investigating critical band rate (bark) distances and variation in vowel quality in peripheral and non-peripheral vowels from a sex-linked developmental perspective

Using a selection of methods, critical band rate (bark) distances and the variation of the 10 vowels were also investigated in greater detail from a sex-specific developmental perspective by examining sex-specific developmental patterns before puberty (ages 7 to 12 years), during puberty (ages 13 and 14 years), after puberty (ages 15 to 18 years), and in adulthood (age 25 to 50 years). A number of acoustic-phonetic dimensions were investigated for both the peripheral (aa, ae, ao, eh, iy and uw) and non-peripheral (ah, er, ih, uh) vowels as a function of age group and sex. Details and the motivation for these dimensions follow: I) F1 and F0 have been identified as major cues to the perceived phonetic openness of a vowel. Therefore, vowel openness expressed as a function of F0 (in Bark), and the degree of standard deviation in the critical band rate of F1 (as an index of the extent of variation in the open-close dimension of vowel quality) was examined (Traunmüller, 1988); II) The critical band rate of F3 can be taken to represent speaker size as it decreases with increasing vocal tract length. The standard deviation values of the critical band rates of F1 index the open-close dimension of vowel quality, those of F2, the front-back dimension of vowel quality, and those of F3, the degree of rhoticity for the vowel er for example. The development of signaling these different dimensions of vowel quality would be reflected in the variation in F1, F2 and F3. Therefore, the dispersion (standard deviation) values of the critical band rates of F1, F2, and F3 expressed as a function of the critical band rate of F3 (vocal tract length and speaker size) were examined (Traunmüller, 1988).; III) Z3-Z0 is approximately the same in the speech of men, women and children, but it decreases with increasing vocal effort. Therefore, it can be taken to represent vocal effort while Z3 can be taken to represent speaker size, as it decreases with increasing vocal tract length. Therefore, the critical band rate (bark) difference between the third formant and F0 (Z3-Z0) was examined as a function of the critical band rate of F3. IV) The range values for F1, F2 and F3 expressed as the difference between the maximum and minimum values of each formant frequency provide information on vowel quality and highlight the role of individual formant frequencies in shaping the vowel quality of peripheral and non-peripheral vowels. For example, peripheral vowels have greater range values in F1 and F2 compared to non-peripheral vowels, whereas a non-peripheral vowel such as er would be expected to showed a greater range in F3 values due to its rhotacized phonetic quality, which is signaled by lowered values in F3 (e.g. Alwan *et al.,* 1997; Dalston, 1975; Espy-Wilson *et al*., 2000). The range in formant frequencies were therefore examined for F1 to F3.

Variations in developmental and adult sex differences as a function of both vowel and formant frequency have been reported (e.g. Bennett, 1981; Busby & Plant, 1995; Fant, 1966, 1975). The differences between female and male formant frequency values were therefore examined from an auditory perspective for each vowel as a function of age group using critical band rate values for F1 to F3 (Traunmüller, 1988).

II. RESULTS

A. *Kn-age* values

The kn-age factor values for all 10 vowels combined, are depicted in Fig. 1 by age and sex for the formant frequencies F1 to F3 (Figs. 1 (a) to 1(c)), and for the overall mean of F1, F2 and F3 (Fig 1(d)). The general developmental trend for both males and females indicates a decrease in the k-age values for all three formant frequencies, as both the males and females between the ages of 7 and 18 years approach the formant frequency values of the adult men and women speakers, respectively. What is worth noting here is that the k1-age values for the females are higher than those of the males from age 15 onwards. In addition, the younger females have higher F1 values compared to the women speakers.

<PLACE FIG 1 about here>

There are sex-specific differences in both the degree and rate of developmental change. For example, when the k-age values were averaged across k1, k2 and k3 ($k_{1,2,3}$-$_{age}$), the difference in the degree of change is marked by a shift from a value of 1.34 at age 7 years, to 1.01 at age 18 years, in the males' data (see Fig 1(d)). This compares with $k_{1,2,3}$-$_{age}$ values of 1.18 and 1.05 for the 7 and 18-year old females, respectively (see Fig 1(d)). The sex-linked differences with respect to the extent of developmental change show that although both the males and females both display maturational patterns during puberty (age 10 to 15 years), these are less prominent for the females.

B. ***Kn-sex*** values

The mean *k-sex* values for all vowels combined, are given in Fig. 2 (a) by formant frequency and age group. The overall k-sex values in Fig. 2 (a) depict discernible sex differences before puberty, and the emergence of more marked differences at age 10 where we see small increases in k2 and k3 factors until age 12. Thereafter, between the ages of 12 and 18 years, the pattern is one of substantial increases with a marked decrease (this was a deviation in the general developmental trend) at age 14, which was due to the males displaying a increase in formant frequencies at age 14 (Lee *et al.*, 1999). The kn-sex factors depicted in Fig. 2 (a) show parallel increases for all three formant frequencies from age 14 years to 16 years, with F1 having the highest values, and F3 the lowest. From age 16 years to 17 years there is no change for k1 (F1) and k2 (F2), but k3 (F3) displays a decrease from 1.13 to 1.10. Between age 17 and 18 years marked increases for k1 (1.25 to 1.30), k2 (1.20 to 1.24) and k3 (1.10 to 1.16) are observed. After this point, k1 and k2 display decreases (k1: 1.30 to 1.20, k2: 1.24 to 1.20) with no change being observed for k3.

<PLACE FIG 2 about here>

When the data for all the children and adults are divided into the four age groups namely pre-puberty (age 7 to 12 years), puberty (13 to 14 years), post-puberty (15 to 18 years), and adults (25 to 50 years), we are able to see the net effect of puberty on sex differences in terms of k-sex factors across all three formant frequencies of the 10 vowels. This net effect is illustrated in Fig 2 (b) which depicts sex-linked developmental trends. Although there is evidence to suggest that there are sex differences before puberty, these become more marked both during, and after puberty. The data given in Fig. 2 (b) also suggest that while a substantial degree of sex differences emerge after puberty for some vowels (e.g. ae, ao, iy and uw in particular - see Fig. 2 (b)), others show a lower proportional increase in kn-sex values after puberty (e.g. aa, ah, er, and uh). The observation that some vowels display greater sex differences in adulthood (e.g. overall k-sex values for aa, ah, eh, and uh - Fig 2 (b)), suggest that some sex-specific patterns continue to unfold during adulthood.

C. *Kn-age* and *kn-sex* values for selected vowels

Fig. 3 depicts the mean k-age values averaged across all three formant frequencies by age and sex for the selected vowels aa, ah, er, ih, iy and uw, and Fig. 4, the k-sex values by formant frequency (F1 (k1), F2 (k2) and F3 (k3)) for the same group of selected vowels. The developmental trend in the k-age factors across all the 6 selected vowels is a general decrease in values with age (see Fig. 3), and for the k-sex factors a general increase with age (see Fig. 4). However, if we examine the data on a vowel-by-vowel basis from a sex-linked developmental perspective we are able to note sex differences in the reduction of k-age values as a function of both age and vowel. For example, there are general decreases in the males' k-age values from age 7 to 13 years, and between age 14 and 15 years for the vowels aa (Fig. 3(a)), ih (Fig. 3 (d)), iy (Fig. 3 (e)) and uw (Fig. 3 (f)) which are more marked when compared to the females data. In addition, after the age of 15, the k-age values for males show a negligible decrease, and therefore only slight decreases in formant frequencies during this period. This contrasts with the female values which display variable patterns of increases and decreases in the k-age values for different vowels after the age of 15 years (see Fig 3). For example, the overall kn-age values for the females decreases gradually from age 7 and reaches a minimum at age 16 for the vowel aa (see Fig. 3 (a)). After this, the values increase for the vowel aa until age 18. The k-sex values for this vowel indicate increases in values after age 14 with the largest of these occurring for F1 (see Fig 4 (a)). In addition, the females' k-age values averaged across all three formants for the vowel iy (see Fig 3 (e)) display an increase at age 16, followed by a decrease at age 17, and finally an increase at age 18. The k-sex values for iy (see Fig 4 (e) also suggest as for the vowel aa, increases in values from age 14 years, with again the highest and lowest values being observed for F1 and F3 respectively.

Further sex-specific differences are exemplified by the vowel uw which displays the highest kn-sex values for the post-puberty group (see Fig 2 (b) and Fig 4 (e)). This pattern is reflected in the females' k-age values and k-sex values for the vowel uw (Fig. 4 (f)). If we focus on the male patterns for the kn-age values of uw in Fig. 3 (f), these are generally similar to those patterns for the other vowels depicted Figs 3 (a) to (e). That is, with the exception of the increase at age 14, there is a decrease with age towards the adults' values, reaching the adults values at age 17. This pattern is rather different from that of the females who show the lowest kn-age values for uw at age 17 which never approaches 1.0 after this point, but in fact increases markedly (see Fig 3 (f)). This pattern suggests that the formant frequencies of the 18 year-old females are significantly higher than those values for the adult females, and also explains the high k-sex values for uw observed for k1 (1.42) and k2 (1.55) at age 18, compared to the much lower values for the adults (k1-1.20; k2-1.17 - see Fig 4 (f)). The net effect of this greater sex difference in the post-puberty group compared to the adult group is depicted in Fig 2 (b).

D. Vowel spaces and critical band rate (bark) distances

The mean distances of all vowels of each sex and age speaker centroid in the F1-F0/F2-F1 vowel space are illustrated in Fig. 5 (a) by age and sex. As seen in Fig. 5, the mean distances for the males and females both show an overall developmental trend of decreasing mean distances with age. However, upon closer examination of the data, we are able to observe that there are some sex-specific developmental differences in the mean distances from the vowel-group centroid. For example, the mean distances from the vowel-group centroids are similar for both the males and females for the age groups: 7, 10, 16 and 18 years. However for the 8-year olds, 17-year olds and the adults, the females display larger mean distances from the vowel-group centroids than the males. This contrasts with the data for the 11, 12- and 14-year olds, which display larger mean distances from the vowel centroids for the males. If we examine the mean distances from the speaker centroids in the pre-puberty, puberty, post-puberty and adult groups, sex-specific effects are observed as a function of age group. For example, the males display a gradual decrease in the mean distance from the speaker centroid, whereas the females display a decrease from pre-puberty to puberty, but subsequent increases thereafter (Fig 5 (b)).

<PLACE FIG 5 about here>

The distances of each vowel from the speaker centroid for the males and females in the F1-F0/F2-F1 vowel space are given in Table I, and depicted in Fig. 6 for the adults (25 to 50 years). What is apparent here is that the women display a more peripheral vowel space than the men. If we define the outer bounds of the monophthongal vowel space using the peripheral vowels iy, uw, ao, ae and aa, the women occupy a larger acoustic space than the men in the F2-F1/F1-F0 dimension. For example, the women display a greater degree openness for the vowel aa, and a greater degree of frontness and constriction for the vowel iy. The female adults also display greater distances from the vowel centroid than their male peers, for nine out of the ten vowels and for all vowels combined, which was found to be significant for the ten vowels using a paired t-test ($t(9)=3.570$, $p<.01$) (see Table I).

<PLACE Table I and FIG 6 about here>

The results of the vowel openness parameter expressed as a function of the fundamental frequency (in Bark) and the degree of standard deviation (dispersion) in the critical band rate of F1 is illustrated as a function of age group and sex in Fig. 7 , for the peripheral vowels (left), and the non-peripheral vowels (right). The females display a decrease in F1 dispersion between pre-puberty and puberty with subsequent increases between post-puberty and adulthood for both vowel sets. This contrasts with the males who show a decrease in F1 dispersion between pre-puberty and puberty, with only slight increases for the same age intervals. These results agree with the developmental data reported by Traunmüller (1988). In addition, the peripheral vowel set displays higher dispersion values compared to the non-peripheral vowels.

<PLACE FIG 7 about here>

The degree of variation in vowel formants as a function of age group and sex, expressed as the dispersion (standard deviation) of the critical band rates of F1, F2 and F3 and the critical band rate of F3 for both the peripheral and non-peripheral vowels is depicted in Fig. 8. All three formant frequencies display sex-specific developmental differences (Figs. 8 (a), (b), and (c)). For example, both the males and females show a decrease in the critical band rate dispersion (standard deviation) from pre-puberty to puberty for both F1 and F2. However, between post-puberty and adulthood, the females exhibit more marked increases in the critical band rate dispersion than the males for both the peripheral and non-peripheral vowels. The women also display higher mean critical-band rate dispersion values for F1 compared to the men for both vowel sets (Fig. 8 (a)), and the pattern for the peripheral vowels replicates those described by Traunmüller (1988) for a set of peripheral Japanese vowels. The women also display a larger increase in the dispersion of F2 values than the men from post-puberty to adulthood for both vowel sets (Fig. 8 (b)), and the ontogenetic development of sex differences in the F2 dispersion patterns for the peripheral vowels are also similar to the peripheral Japanese vowels reported by Traunmüller (1988). For F3 (see Fig. 8 (c)) there are also sex-specific developmental differences for both vowel sets, but the pattern of these differences varies with the vowel set in question. For example, the peripheral vowels indicate that both the males and females display slight increases in the critical band-rate dispersion between pre-puberty and puberty, and between puberty and post-puberty, and slight decreases between post-puberty and adulthood. This contrasts with the non-peripheral vowels which show more sex-specific differences. For example, the males show a decrease, but the females an increase, between pre-puberty and puberty. In addition, although both the females and males show an increase in the dispersion values of F3 between post-puberty and adulthood, this is more marked for the females (see Fig 8 (c)). What is worth noting at this point is that the dispersion values of F3 are higher for the non-peripheral vowels compared to the values peripheral vowels, due to the inclusion of the rhotacized vowel er in the non-peripheral vowel set.

<PLACE FIG 8 about here>

The relationship between speaker size and vocal effort of the 10 vowels expressed as a function of the third formant (Z3: Bark) and the difference between the third formant and F0 (Z3-Z0: Bark) (after Traunmüller, 1988) is depicted in Fig. 9 by age group and sex for both the peripheral and non-peripheral vowel sets. An increase in vocal tract length is indexed by a decrease in F3, and an increase in vocal effort, by a decrease in the value of Z3-Z0 (Bark). These data illustrate sex-specific developmental differences in both vocal tract length (F3: Bark) and vocal effort (Z3-Z0: Bark). For both vowel sets, the females display a pattern of increase in both the dimensions of speaker size and vocal effort from pre- through to post-puberty, the net result of which is more marked for the non-peripheral vowel set that includes er. Although the males also display a net increase in vocal effort from pre- to post-puberty, this developmental increase is less marked than that observed for the females. In addition, between post-puberty and adulthood, the males display higher increases in vocal effort compared to the females for both the peripheral and non-peripheral vowels (see Fig 9). When the vowel sets are compared, levels of vocal effort for all three age groups are greater for the non-peripheral vowel set that includes er. With respect to vocal tract length, the non-peripheral vowels also display both marked decreases in F3 (Bark) and therefore, a marked increase in vocal tract length, compared to the peripheral vowels.

<PLACE FIG 9 about here>

The ranges in formant frequency values (F1 to F3 in Bark) across all vowels are illustrated in Fig. 10 for both vowel sets for the four age groups (pre-puberty: 7 to 12 years; puberty: 13 and 14 years; post-puberty: 15 to 18 years; adults: 25 to 50 years) by sex. These data show larger range values for both F1 and F2 for the peripheral vowels. This contrasts with the data for F3 which show larger range values for the non-peripheral vowels, a pattern that once again can be explained by the inclusion of er in this vowel set.

<PLACE FIG 10 about here>

The tonotopic distances between female and male formant frequencies (F1 to F3 in Bark) across all vowels are depicted in Fig. 11 for the four age groups (7 to 12 years; 13 and 14 years; 15 to 18 years; 25 to 50 years). These data display that although there are sex-specific developmental patterns, these are dependent upon both the formant frequency and the vowel. For example, all three formant frequencies display some sex differences before puberty, but some of these differences are greater for specific formants and vowels (e.g. F1 of iy (Fig. 11 (a)), and F3 of er (Fig.11 (b)). In addition, although an increase in male-female differences continues to occur from puberty to post-puberty for F1, F2 and F3, these sex differences appear to become less marked between post-puberty and adulthood for some of the data (e.g. F1 as shown in Fig 11 (a)).

III. DISCUSSION

The aim of this paper was to re-examine the fundamental frequency and formant frequency data presented by Lee *et al.* (1999) from a sex-specific developmental perspective. The re-examination of the data adopted two basic approaches; examining sex-linked developmental formant frequency differences as a function of age and sex using formant scaling (Fant, 1966, 1975); and investigating sex-specific developmental patterns in fundamental frequency and formant frequencies using a number of acoustic-phonetic dimensions based on the critical band rate (Bark) scale (Traunmüller, 1988, 1990). Both approaches revealed a range of sex differences which were developmental in nature. These are discussed below.

A. Formant scaling k-age and k-sex factors

A number of points emerge from this reexamination of Lee *et al.*'s (1999) data using k-age and k-sex values based on Fant's method (1966, 1975). The mean k-age values for F1, F2 and F3 showed a general decrease with age with the males displaying greater decreases than the females (see Fig 1). This trend reflects the general pattern of developmental sex differences in the maturation of the vocal tract (Fitch and Giedd, 1999). In addition, the patterns in Fig. 1 indicate that from age 10, both the males and females display a more marked decrease in formant frequencies, which coincides with the onset of the peripubertal stage at age 10.3 years, identified by Fitch and Giedd (1999). Notably, the decrease in k-age values appears to be less marked after age 15 years. This suggests that in the postpubertal stage (~15 years to ~18 years), overall changes in formant frequencies are of a smaller magnitude than those which occur during puberty.

The k-age values also show evidence of sex-specific differences for the formant frequencies of the vowels. For example, the male k-age values decrease with age, and by age 18 years, they are close to a scale factor of 1.0 for F1 (1.01), F2 (1.01) and F3 (1.02). This contrasts with the data for the females, who also show this decrease with age, but by age 18 years, only k3 is close to 1.0 (1.02), whereas k1 and k2 have values of 1.10 and 1.04, respectively. The k-age data for the selected vowels in Fig. 3 suggest that this pattern is the result of the 18 year-old females' higher k-age values for er, iy and uw relative to the adult female group. Such marked differences at age 18 years cannot be explained solely in terms of maturational differences of the vocal tract alone. It is therefore more likely that the phonetic quality of uw samples produced by the 18-year olds was different, and on average, more palatalized, less rounded and more open than those of the adult women. This raises the role of sociophonetic factors as possible key influences in determining the phonetic quality of vowel formant frequencies (e.g. Byrd, 1992, 1994; Henton, 1995; Lee *et al.*, 1999). It is suggested that the phonetic quality of the vowel uw, may be an example of sociophonetic and/or accent variation in the 18 year-old females. An additional observation worth noting here is that the 18 year-old females also displayed the highest fundamental frequency values within the post-pubertal and adult female groups. The question therefore, is whether the adults (25 to 50 years) simply came from a different accent group, or whether there were variations in stylistic conventions between the postpubertal and adult groups. Unfortunately, we are not provided with a detailed age, gender and accent breakdown to ascertain this, and therefore would be an interesting factor to explore further. Furthermore, because the adult group spans 25 years, it is not unreasonable to suggest that there may be further age- and sex-specific differences within this group. Given this, it would be worth investigating whether age-related sex differences are present between the younger adults (e.g. 25-35 years) and older adults (e.g. 40-50 years). If age-related differences were found, they would supplement evidence reported for changes in speech and voice characteristics during the adult lifespan (e.g. Decoster and Debruyne, 1997, 2000; Xue *et al.*, 1999).

The presence of sex differences before puberty replicates the findings of other studies (e.g. Bennett, 1981; Busby and Plant, 1995; Eguchi and Hirsh, 1969; White, 1999). These sex differences become more marked after puberty (see Fig 2 (b)), despite the drop at age 14 years, which is due to the males displaying higher formant frequencies (see Fig. 2 (a)). Lee *et al.* (1999) explain this drop as being the consequence of maturational processes. The developmental trend of k-sex values reflects sex-specific patterns in the maturation of the vocal tract (Fitch and Giedd, 1999), and the k-sex values as noted in the Results above (sections B. and C.) are both formant frequency dependent (see Figs. 2 (a), (b), (c)) and vowel dependent (see Fig. 2 (b) and Fig 4). These patterns suggest the emergence of non-uniform sex differences in the vocal tract morphology of males and females which therefore affects the degree of variation in formant frequencies as a function of sex and vowel context. The k-sex factors for F1, F2 and F3 (see Fig 2 (a)) for example, reflect the emergence of sex differences in the pharynx, oral cavity and total vocal tract length. This is supported by Fitch and Giedd (1999) who report significant sex differences in the relative length differences between the oral and pharyngeal cavities, with greater mean sex differences in the postpubertal subjects (12.9 mm) compared to those of the peripubertal subjects (7.5 mm). This therefore provides some indirect evidence to explain why front vowels such as ae and iy in Lee *et al.'s* data exhibit the bulk of their increases in kn-sex values after puberty. The degree of the sex differences exhibited by the vowel uw, in contrast to the other selected vowels however (see Fig 2 (b)), suggests that vocal tract length alone, is not sufficient in explaining the extent of some sex-specific effects, and that other factors related to accent, speaking style or sociophonetic influences may be responsible for some speaker sex differences. A similar finding is reported by Traunmüller (1988) who observed variations in vowel quality for some women speakers in a Japanese data set.

On the basis of evidence which suggests that the male vocal tract continues to go through maturational changes (Fitch and Giedd, 1999), one might expect to find more dramatic drops in the formant frequencies of the males from age 15 in Lee *et al*.'s (1999) data, and therefore larger kn-sex values than those reported here (see Figs 2 (a) and 2 (b)). A marked lowering of the male formant frequencies after age 15 years does not occur, which is a point that Lee *et al*. (1999) raise in their paper. This suggests once again, that the physical length of the vocal tract alone, may not be sufficient in explaining the male formant frequency patterns of the 10 vowels after age 15 years, and that other factors (e.g. physiological, sociocultural, stylistic conventions) may be responsible for these and other sex-specific patterns (e.g. Byrd, 1992, 1994; Hasek *et al.*, 1980; Henton, 1995; Lee *et al*., 1999; Mattingly, 1966; Traunmüller, 1984, 1988).

B. Fundamental frequency and formant frequency patterns using the critical band rate (Bark) scale

The examination of fundamental and formant frequency patterns using a selection of acoustic phonetic parameters in the bark scale reveals the ontogeny of sex differences in the phonetic quality of the 10 monophthongs reported by Lee *et al.* (1999). For example, the vowel spaces defined by F2-F1 versus F1-F0 display evidence of sex-specific patterns, which are developmental in nature. Different sex-specific patterns are observed before, during and after puberty and by adulthood, the women display a more peripheral vowel space and therefore a greater phonetic distinctiveness in vowel quality than the men (see Table 1, Figs. 5 (a), 5 (b), and 6). The ontogeny of this sex difference in phonetic distinctiveness is explained if we examine the acoustic-phonetic dimensions of vowel quality that were investigated using the bark scale. For example, the degree of vowel openness expressed as a function of fundamental frequency (in Bark) and the degree of standard deviation in the critical band rate of F1 showed the adult women displaying an increase in the dispersion of F1 (Bark) for both peripheral and non-peripheral vowels compared to the 15 to 18 year olds (Figs 7 and 8 (a)). This increase in the dispersion of F1 is not observed for the men speakers and cannot be accounted for as a function of either F0 (Fig, 7) or F3 (Fig 8 (a)), which therefore suggests that the women in Lee *et al.'s* study must have been producing their vowels with greater acoustic-phonetic distinctiveness, by may be adopting more extreme articulatory postures than the men (e.g. greater openness and closeness). This increased phonetic distinctiveness also explains the higher range values observed for the women's F1 values (Fig. 10 (a)), and the greater openness of aa depicted in Fig. 6. Similarly, if we examine the phonetic quality of the vowels in terms of the front-back dimension, the adult women display increases in the dispersion values for F2 (Fig. 8 (b)), and increases in the range values for F2 (Fig. 10 (b)) compared to the 15 to 18 year olds. These patterns are particularly marked for the peripheral vowels, and again suggests that the women are displaying a greater degree of phonetic distinctiveness for this group of vowels compared both to the 15 to 18 year old females and the men within this dimension of vowel quality. The contribution of F3 to vowel quality with respect to both dispersion and range values appears to be more significant for the non-peripheral vowels which is largely due to the inclusion of the rhotacized vowel er, which is characterized by lower F3 values (Alwan *et al.*, 1997; Dalston, 1975; Espy-Wilson *et al*., 1997, 2000). What is interesting to note is that although the adult men and women both display increases in the dispersion values of F3, the extent of this increase between post-puberty and adulthood is more marked for the adult women (Fig. 8 (c)). This is further evidence to suggest that the adult women are producing vowels which are more distinct in their acoustic-phonetic dimensions. What is interesting to note at this point is that the data for the F1, F2 and F3 dispersion values for the peripheral vowels are similar to those reported by Traunmüller (1988) for a Japanese data set. These cross-linguistic similarities in sex-specific patterns in speech therefore suggest that at least some linguistic behavior in males and females can be explained by underlying physiological differences between the sexes.

The data for F1 and F2 discussed above go some way in explaining both the greater distances from the speaker centroid, and the more peripheral vowel spaces for the women speakers in terms of the open-close acoustic-phonetic dimension of vowels (Table 1, Fig. 6). The pattern of larger and more peripheral vowel spaces for women replicates previous findings (e.g. Deterding, 1997; Henton, 1983, 1995; Rosner and Pickering, 1994; Traunmüller, 1988), but more importantly, the reexamination of Lee *et al.*'s (1999) data reveals that sex differences in vowel space appear to emerge with development, from pre-adolescence to adulthood. Physiological factors and anatomical constraints due to sex-specific maturational differences may be instrumental in shaping the more peripheral vowel spaces displayed by women (Traunmüller, 1984, 1988). However, sociophonetic factors may also be playing a part in influencing the development of learned sex-specific speech behaviors. This suggestion is supported by evidence which suggests that the auditory space of men and women varies across languages, and that there are therefore language-specific stylistic factors that may determine some habitual speech settings (see Henton (1995) and Rosner and Pickering (1994) for examples of data from a variety of languages). The extent to which sociophonetic influences appear to be culturally determined should therefore be acknowledged in light of these cross-language data.

An issue related to sociophonetic factors and stylistic convention, is the extent to which speech behavior(s) are shaped by a particular scenario. For example, a cross-language study of American, Russian and Swedish (Kuhl *et al.*, 1997) found evidence of mothers producing "more extreme" vowels in infant-directed samples, compared to those in adult-directed samples. In addition, studies by Byrd (1992, 1994) report evidence to suggest that women may adopt a speech style that displays less phonetic reduction in more formal contexts, such as experimental settings. Therefore, the extent to which the experimental scenario influenced the speech style of the women in Lee *et al.*'s study (1999), to produce their more peripheral vowel spaces, remains both an important and an interesting question. What emerges from this discussion however, is that a combination of anatomical, physiological, sociophonetic/cultural and idiosyncratic factors are all likely to play some role in determining speaker sex differences, and their developmental patterns.

The relationship between vocal tract length and vocal effort of the 10 vowels expressed as a function of the third formant (Z3: Bark) and the difference between the third formant and F0 (Z3-Z0: Bark) show sex-specific developmental patterns for both vowel sets. Although both the females and males display increases in the vocal effort parameter with age for both vowel sets as decreases in Z3-Z0, the males display more significant increases in vocal effort from post-puberty to adulthood, which is largely due to their lower F3 values compared to the females. In addition, the increases observed for vocal effort were found to be more marked for the non-peripheral vowels, which can be explained by the inclusion of the rhotacized vowel er in this vowel set which has lowered F3 values. The dimension of speaker size indexed as an inverse relationship to F3 shows that the development of rhoticity, and lower F3 values is therefore instrumental in contributing to decreases in Z3-Z0, and therefore increases in 'speaker size' (see Fig. 9 (right side)). Of particular note is the markedly lower F3 values for the adult men (13.84 Bark) compared to the adult women (14.87 Bark) for the non-peripheral vowel set that includes er. The distinctive 'dip' or lowered F3 values for the rhotacized vowel is likely to be the result of similar articulatory configurations that are typically reported for /ɹ/ (e.g. Alwan *et al.*, 1997; Espy-Wilson *et al.*, 2000) and replicates previously reported speaker sex differences in adults for the formant frequency values of /ɹ/ (Westbury *et al.*, 1998).

The articulatory configurations for /ɹ/ include pharyngeal, palatal and labial constrictions (e.g. Alwan et al., 1997; Espy-Wilson *et al.*, 1997, 2000), and the creation of a sub-lingual cavity anterior between the palatal and lip constriction (e.g. Espy-Wilson and Boyce, 1999). The net effect of this sub-lingual cavity is to increase the volume of the oral cavity, which therefore lowers the frequency of F3. On this basis, the presence of a sex difference before puberty, for the mean value of F3 (Bark) for the vowel er (see Fig. 11) suggests that there may already be sex differences before puberty in the volume of the oral cavity which includes the sub-lingual cavity, which continue to increase during and after puberty. In addition, the presence of speaker sex differences in the lengths of the lip segments of pre-pubertal boys and girls (Fitch and Giedd, 1999) may also help to explain the presence of this sex difference before puberty.

The sex differences in the MRI data of vocal tract morphology reported by Fitch and Giedd (1999) also highlight the sex differences in vocal tract length and the proportionately longer pharynx of males after puberty. Non-uniform sex differences in the vocal tract are capable of explaining the non-linear increase in the tonotopic distance between female and male formant frequency values of different vowels. For example, greater female-male tonotopic distances of F1 for aa, ae, ao and ah after puberty (see Fig. 11 (a)) could be attributed to marked growth in the pharyngeal cavities of postpuberty males, and a similar explanation could be proposed for the marked increase in female-male differences for F2 from puberty to postpuberty for the palatal vowel iy. The fronted quality of uw (produced by the 17 and 18 year-olds), which was suggested to be a consequence of accent/sociophonetic factors may also be explicable in these terms. However, in addition to non-uniform sex differences in vocal tract length, sex differences in vocal tract volume also require some investigation. Sex-specific differences in vocal tract volume may provide us with additional information on the emergence of some of the more marked sex-differences in specific formants of specific vowels, such as F3 in er (see Fig 11 (c)). What is worth highlighting at this stage is that even before puberty, there is an appreciable tonotopic distance between the F3 values of females and males (Fig. 11 (c)), an observation which further stresses that vocal tract length alone may not be responsible for all the sex differences observed for vowel formant frequencies. The fact that F1 shows a decrease in the frequency differences between the adult men and women compared to the postpubertal (15-18 years) males and females is due to decreases in F1 values for the adult women, and suggests that there may be age-specific changes occurring in the vocal tracts of the older females in this group. This suggestion is speculative but is not unreasonable in light of recent evidence which shows that there are differences between the vocal tract configurations and resulting formant frequencies of 33-48 year old and 50-66 year old women (Xue *et al.*, 1999). This further highlights the need for further information on the demographic profile of the adult men and women reported in Lee *et al.* (1999).

Further research into human vocal tract morphology and acoustic correlates, together with a longitudinal perspective of speech development will provide valuable insights into age- and sex-specific developmental formant frequency patterns. Such a longitudinal perspective would also assist in shedding further light on specific aspects of individual differences in the development and maturational process of speech characteristics (Smith and Kenney, 1998). In addition, a longitudinal perspective may go some way in explaining some of the between-subject variability observed in cross-sectional studies, and the instability of speech patterns during periods of accelerated maturation and growth around and during puberty (Lee *et al.*, 1999), and highlight those changes that may be occurring across the adult lifespan (e.g. Decoster and Debruyne, 1997, 2000; Xue *et al*., 1999). Such a perspective may also reveal the extent to which physiological, sociophonetic, cultural and stylistic conventions are responsible for sex differences in formant frequencies and the acoustic-phonetic quality of vowels which cannot be explained by developmental sex-linked differences in vocal tract morphology alone (e.g., Busby and Plant, 1995; Fant, 1966, 1975; Fitch and Giedd, 1999; Lee *et al.*, 1999; Traunmüller, 1988, 1990).

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FOOTNOTES

[1]The data from the 5 and 6 year olds were excluded from this re-examination, as the vowel data were based on words produced in isolation. This contrasted with the source of other age groups, where vowel data were based on words spoken in carrier phrases. The exclusion of these data therefore meant that data from 13 age groups were included in this study (7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 year-olds, and the adults (25 to 50 years)).

[2] These alphabetic symbols are also used to represent the monophthongs (vowels) in all tables and figures, however the equivalent IPA symbols for reference to readers are as follows: aa (/ɑ/ as in *pot*); ae (/æ/ as in *bat*); ah (/ʌ/ as in *but*); ao (/ɔ/ as in *ball*); eh (/ɛ/ as in *bet*); er (/ɝː/ as in *bird*); ih (/ɪ/ as in *bit*); iy (/iː/ as in *bead*); uh (/ʊ/ as in *put*); uw (/uː/ as in *boot*). The term *vowel* will be used to complement the term 'monophthong' from this point onwards.

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Table I. Distances from F2-F1/F1-F0 monophthong speaker centroid for the adult group (25 to 50 years) for each vowel by sex* as a measure of vowel space.

Centroid Value for F2-F1 (x)/F1-F0 (y) by sex	Sex	aa	ae	ah	ao	eh	er	ih	iy	uh	uw	All vowels
F: x=6.05, y=3.65	F	3.57	1.39	1.66	3.90	.95	.64	2.49	5.92	.69	1.99	2.32
M: x=5.69, y=3.77	M	3.15	1.32	1.63	3.45	.87	.56	2.32	5.62	.69	1.78	2.14

* paired t-test for all 10 vowels to test for sex differences (F-M): t(9)=3.570, p<.01

FIGURE CAPTIONS

FIG. 1. (a) Mean k1-age (F1) values across all 10 vowels by age and sex; (b) Mean k2-age (F2) values across all 10 vowels by age and sex; (c) Mean k3-age (F3) values across all 10 vowels by age and sex; (d) Mean k-values averaged for k1, k2 and k3 ((F1 + F2 +F3)/3) across all 10 vowels by age and sex.

FIG 2. (a) Mean kn-sex values for the first three formant frequencies (F1, F2 and F3) averaged across all vowels by age group. (b) Mean k-sex values averaged across all three formant frequencies by vowel for the four age groups (7-12 years, 13-14 years, 15-18 years, and 25-50 years).

FIG 3. Mean k-age values averaged across three formant frequencies ((F1 + F2 +F3)/3) by age and sex for the selected vowels, (a) *aa*, (b) *ah*, (c) *er*, (d) *ih*, (e) *iy*, and (f) *uw*.

FIG 4. Mean k-sex values by age group and formant frequency (F1, F2, F3), for the selected vowels, (a) *aa*, (b) *ah*, (c) *er*, (d) *ih*, (e) *iy*, and (f) *uw*.

FIG 5. (a) Mean distance of vowels from the speaker centroid of the male and female speakers by age; (b) Mean distance of vowels from the speaker centroid by sex for the four age groups (7-12 years, 13-14 years, 15-18 years, and 25-50 years).

FIG 6. Vowel spaces (F1-F0 (Bark)) versus F2-F1 (Bark) for the the men and women adults (25 to 50 years).

FIG 7. Critical band rate standard deviation of F1 plotted against F0 (Bark) for the peripheral vowels (aa, ae, ao, eh, iy, uw) (left), and non-peripheral vowels (ah, er, ih, uh) (right). Values are plotted for the four age groups (7-12 years, 13-14 years, 15-18 years, and 25-50 years) by sex .

FIG 8. Critical band rate standard deviation for (a) First formant frequency (F1), (b) Second formant frequency (F2), (c) Third formant frequency (F3) plotted against the critical band rate of F3 for the peripheral vowels (aa, ae, ao, eh, iy, uw) (left), and non-peripheral vowels (ah, er, ih, uh) (right). Values are plotted for the four age groups (7-12 years, 13-14 years, 15-18 years, and 25-50 years) by sex .

FIG 9. Critical band rate (bark) difference between F3 and F0 plotted against critical band rate (bark) of F3 for the peripheral vowels (aa, ae, ao, eh, iy, uw) (left), and non-peripheral vowels (ah, er, ih, uh) (right). Values are plotted for the four age groups (7-12 years, 13-14 years, 15-18 years, and 25-50 years) by sex .

FIG 10. Ranges in formant frequency values expressed as a function of the difference between the maximum and minimum formant frequency values for (a) F1 (Bark), (b) F2 (Bark) and (c) F3 (Bark). Values are given for the peripheral and non-peripheral vowel sets by age group (7-12 years, 13-14 years, 15-18 years, and 25-50 years), for both females and males.

FIG 11.Critical band rate (bark) differences between female and male formant frequency values for (a) F1, (b) F2, and (c) F3 by vowel and age group (7-12 years, 13-14 years,15-18 years, and 25-50 years).

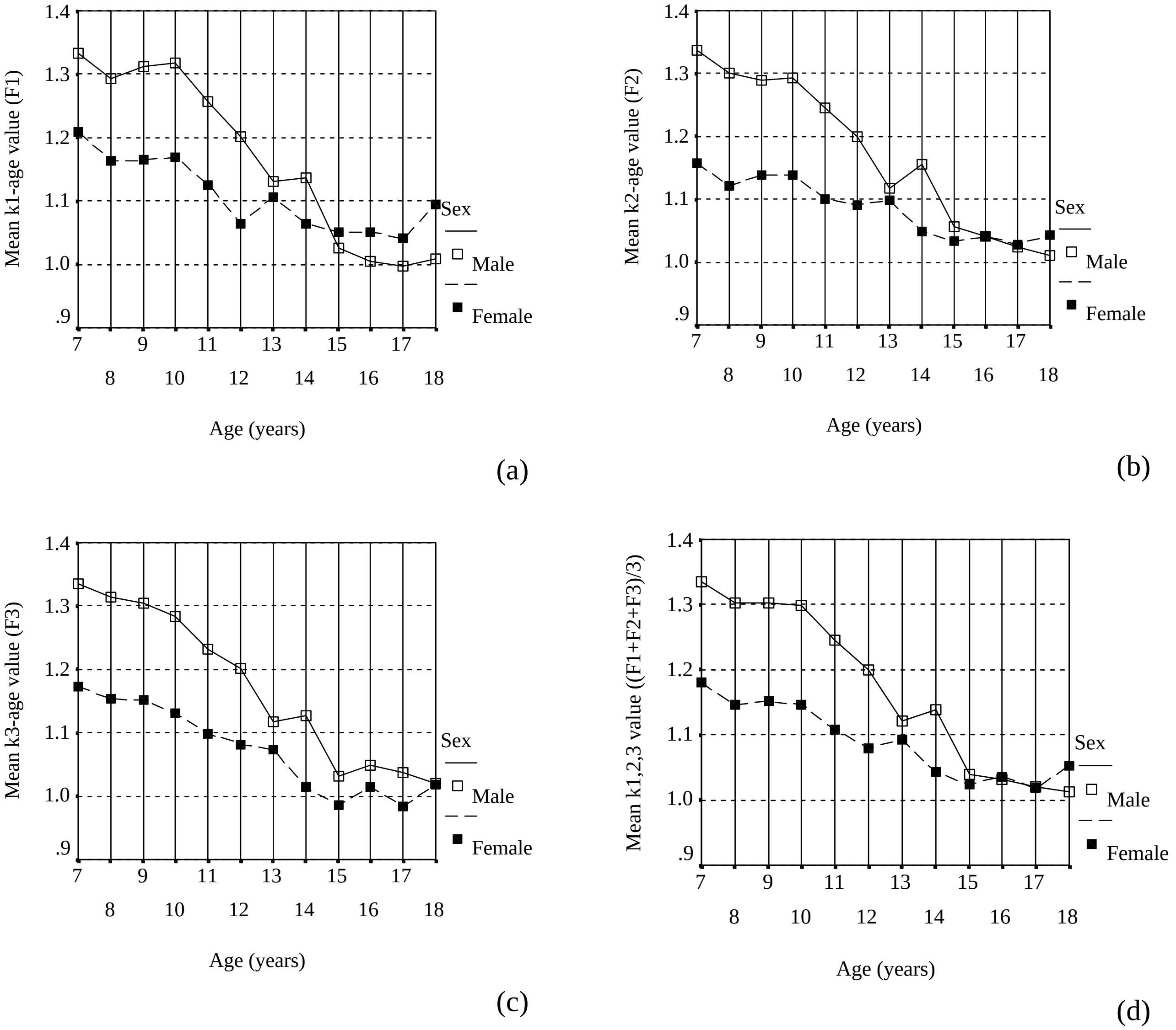
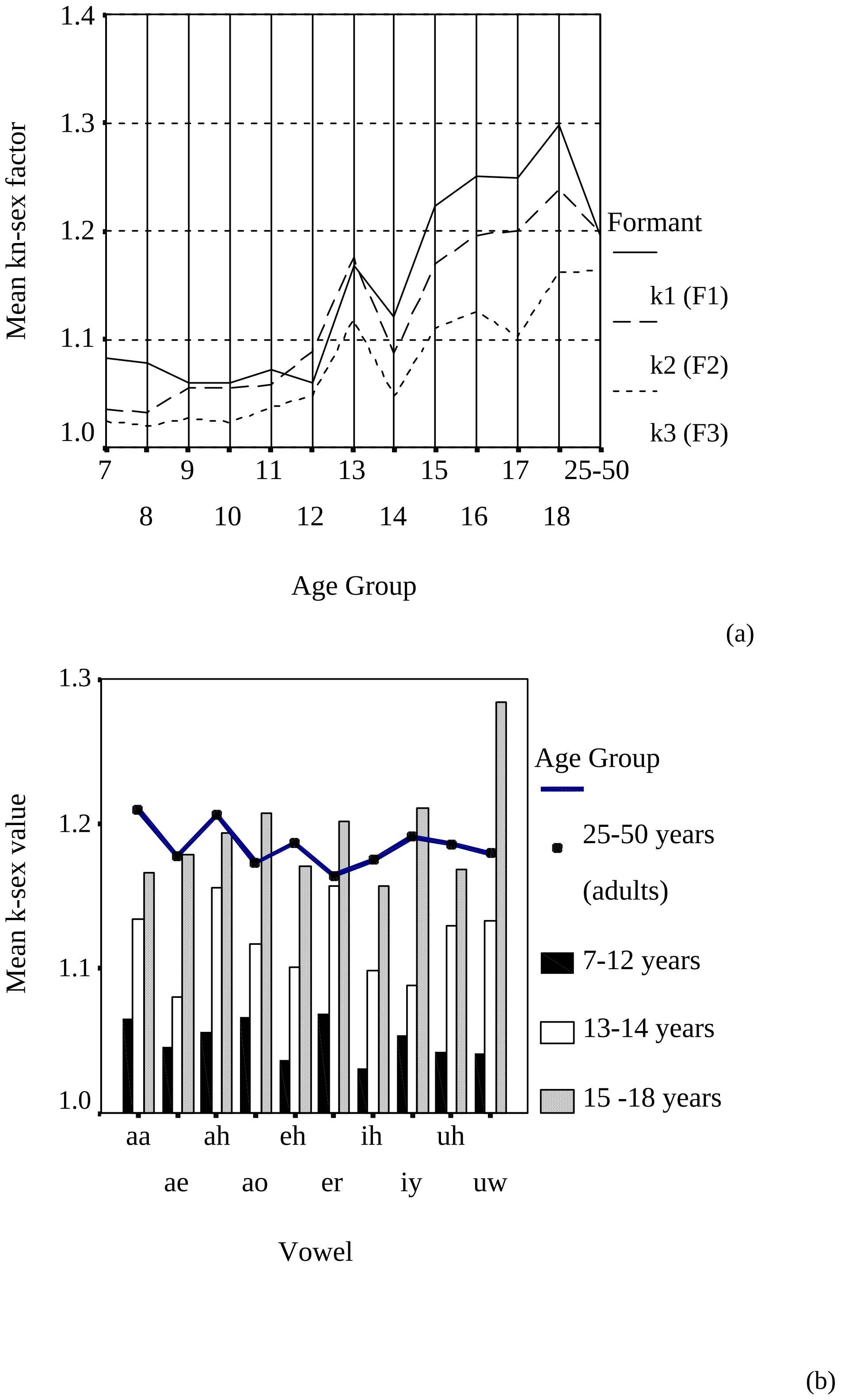

Mean k1-age value (F1)
Mean k2-age value (F2)
Mean k3-age value (F3)
Mean k1,2,3 value ((F1+F2+F3)/3)
1.4
1.3
1.2
1.1
1.0
.9
7
8
9
10
11
12
13
14
15
16
17
18
Age (years)
Sex
Male
Female
(a)
(b)
(c)
(d)

FIG. 1


1.4
1.3
1.2
1.1
1.0
Mean kn-sex factor
7
8
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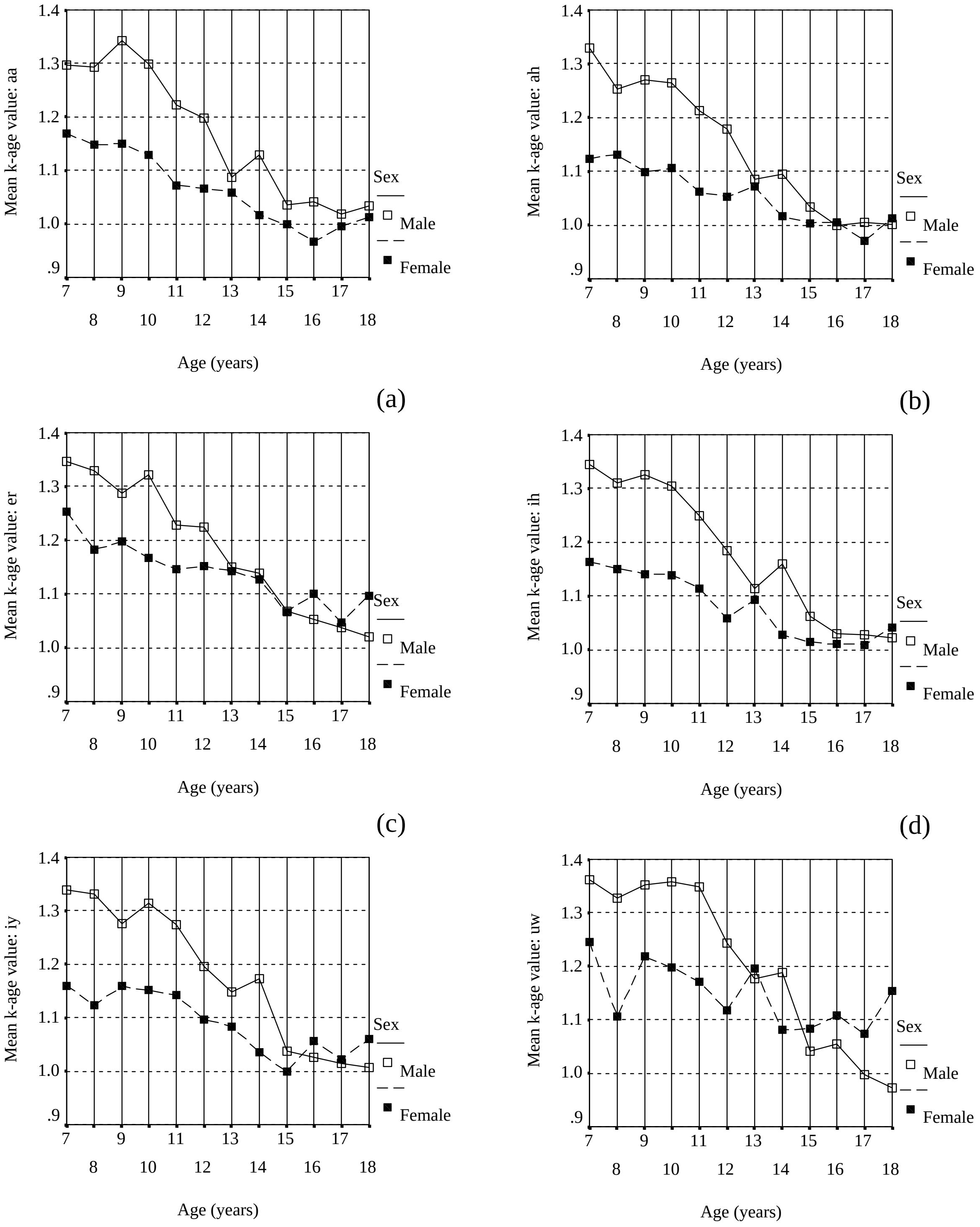
18
25-50
Age Group
Formant
k1 (F1)
k2 (F2)
k3 (F3)
(a)
1.3
1.2
1.1
1.0
Mean k-sex value
aa
ae
ah
ao
eh
er
ih
iy
uh
uw
Vowel
Age Group
25-50 years
(adults)
7-12 years
13-14 years
15 -18 years
(b)

FIG. 2


Mean k-age value: aa
Mean k-age value: ah
Mean k-age value: er
Mean k-age value: ih
Mean k-age value: iy
Mean k-age value: uw
1.4
1.3
1.2
1.1
1.0
.9
7
8
9
10
11
12
13
14
15
16
17
18
Age (years)
Sex
Male
Female

(a) (b) (c) (d) (e) (f)

FIG. 3

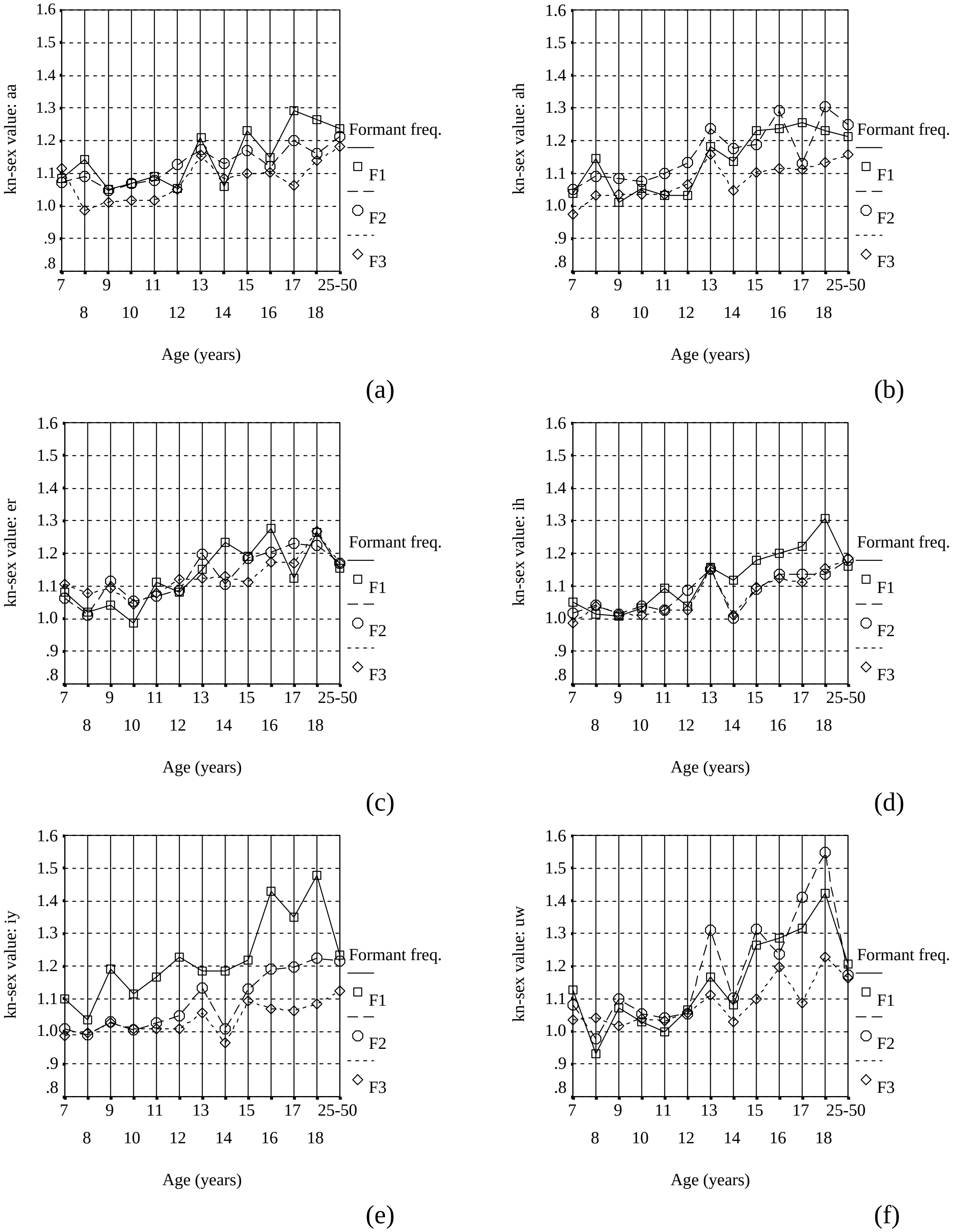

kn-sex value: aa
kn-sex value: ah
kn-sex value: er
kn-sex value: ih
kn-sex value: iy
kn-sex value: uw
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
7
9
11
13
15
17
25-50
8
10
12
14
16
18
Age (years)
Formant freq.
F1
F2
F3
(a)
(b)
(c)
(d)
(e)
(f)

FIG. 4

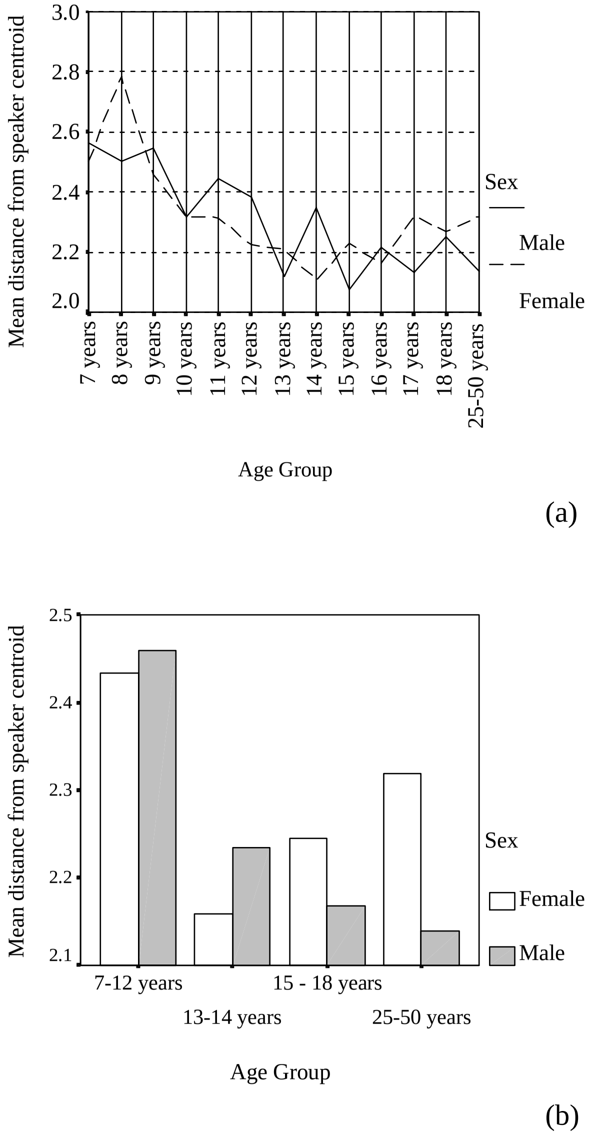

Mean distance from speaker centroid
3.0
2.8
2.6
2.4
2.2
2.0
7 years
8 years
9 years
10 years
11 years
12 years
13 years
14 years
15 years
16 years
17 years
18 years
25-50 years
Age Group
Sex
Male
Female
(a)
Mean distance from speaker centroid
2.5
2.4
2.3
2.2
2.1
7-12 years
13-14 years
15 - 18 years
25-50 years
Age Group
Sex
Female
Male
(b)

FIG. 5

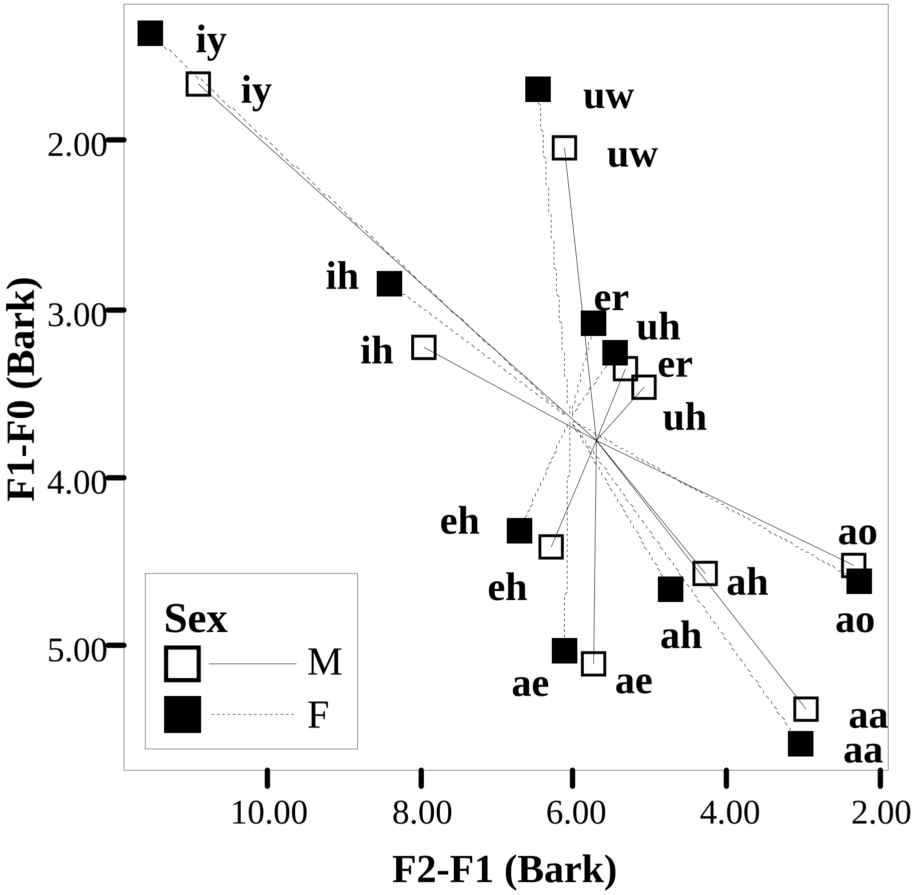

iy
iy
uw
uw
ih
ih
er
uh
er
uh
eh
eh
ao
ah
ao
ah
ae
ae
aa
aa
Sex
M
F
2.00
3.00
4.00
5.00
F1-F0 (Bark)
10.00
8.00
6.00
4.00
2.00
F2-F1 (Bark)

FIG. 6

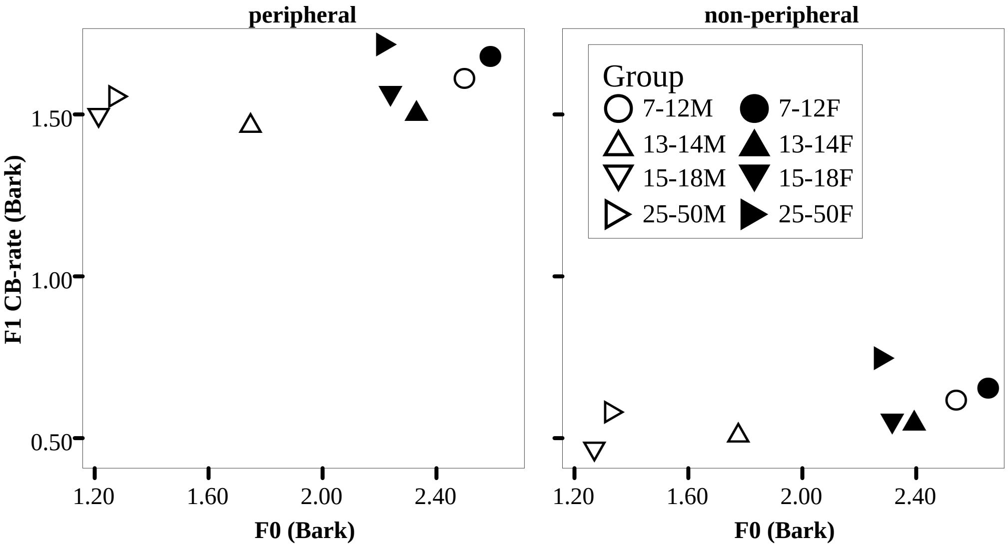
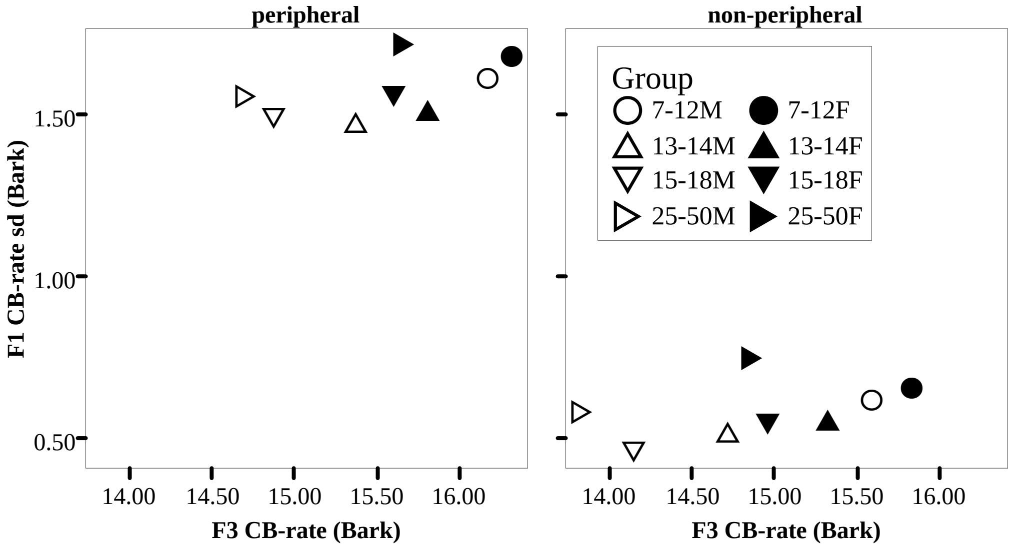
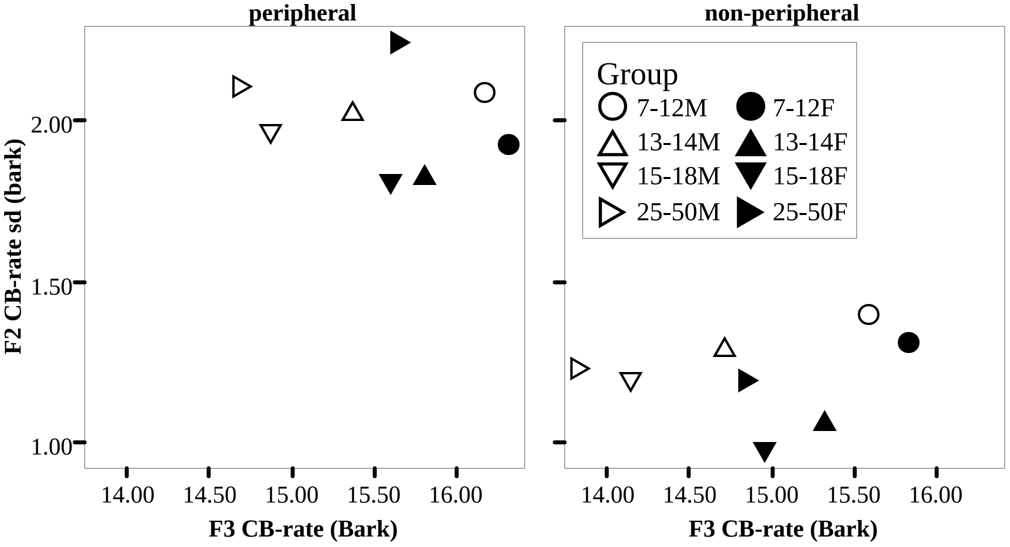

peripheral
non-peripheral
F1 CB-rate (Bark)
1.50
1.00
0.50
1.20
1.60
2.00
2.40
F0 (Bark)
Group
○ 7-12M
● 7-12F
△ 13-14M
▲ 13-14F
▽ 15-18M
▼ 15-18F
▷ 25-50M
▶ 25-50F

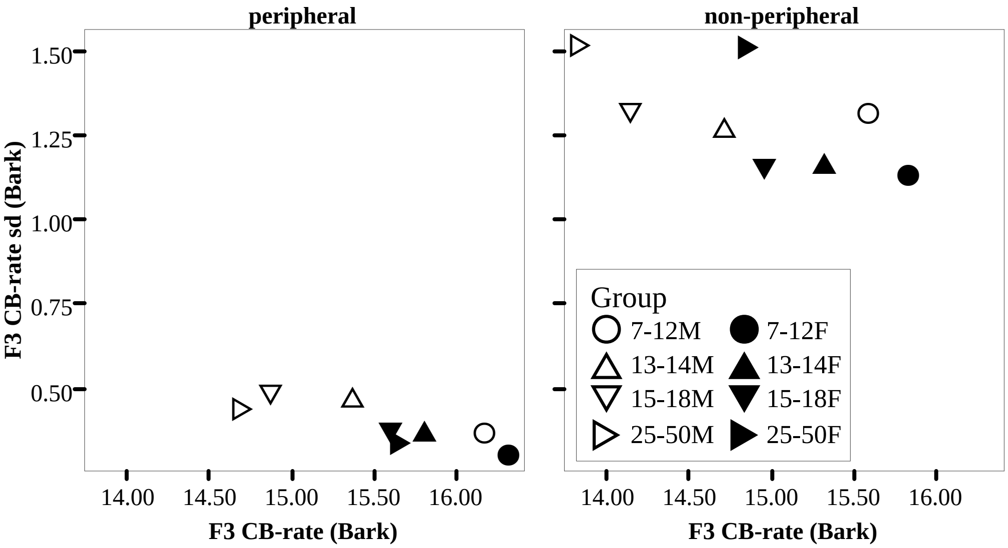
FIG. 7


peripheral
non-peripheral
F1 CB-rate sd (Bark)
1.50
1.00
0.50
14.00
14.50
15.00
15.50
16.00
F3 CB-rate (Bark)
Group
7-12M
7-12F
13-14M
13-14F
15-18M
15-18F
25-50M
25-50F

(a)


peripheral
non-peripheral
F2 CB-rate sd (bark)
2.00
1.50
1.00
14.00
14.50
15.00
15.50
16.00
F3 CB-rate (Bark)
Group
7-12M
7-12F
13-14M
13-14F
15-18M
15-18F
25-50M
25-50F

(b)


peripheral
non-peripheral
F3 CB-rate sd (Bark)
1.50
1.25
1.00
0.75
0.50
14.00
14.50
15.00
15.50
16.00
F3 CB-rate (Bark)
Group
7-12M
7-12F
13-14M
13-14F
15-18M
15-18F
25-50M
25-50F

(c)

FIG. 8

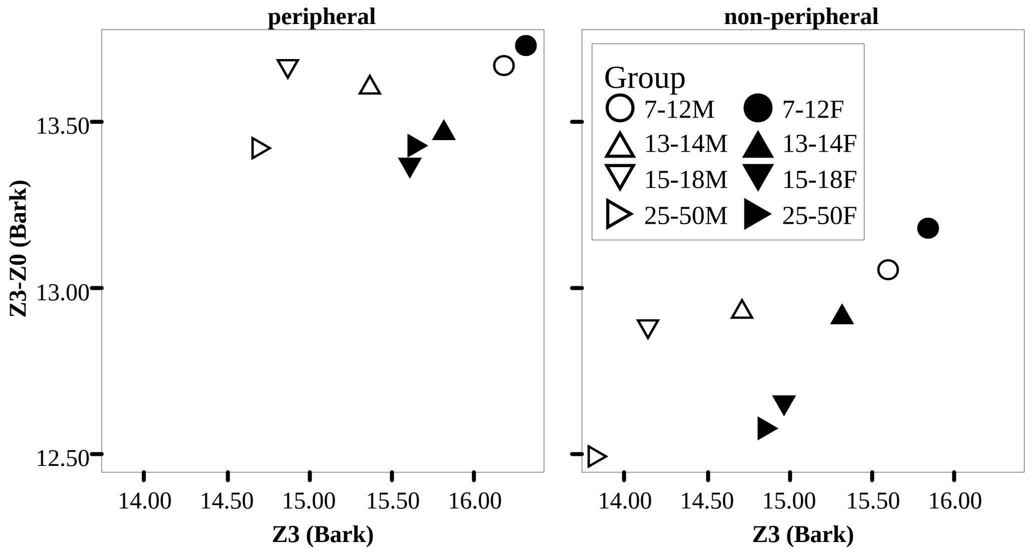
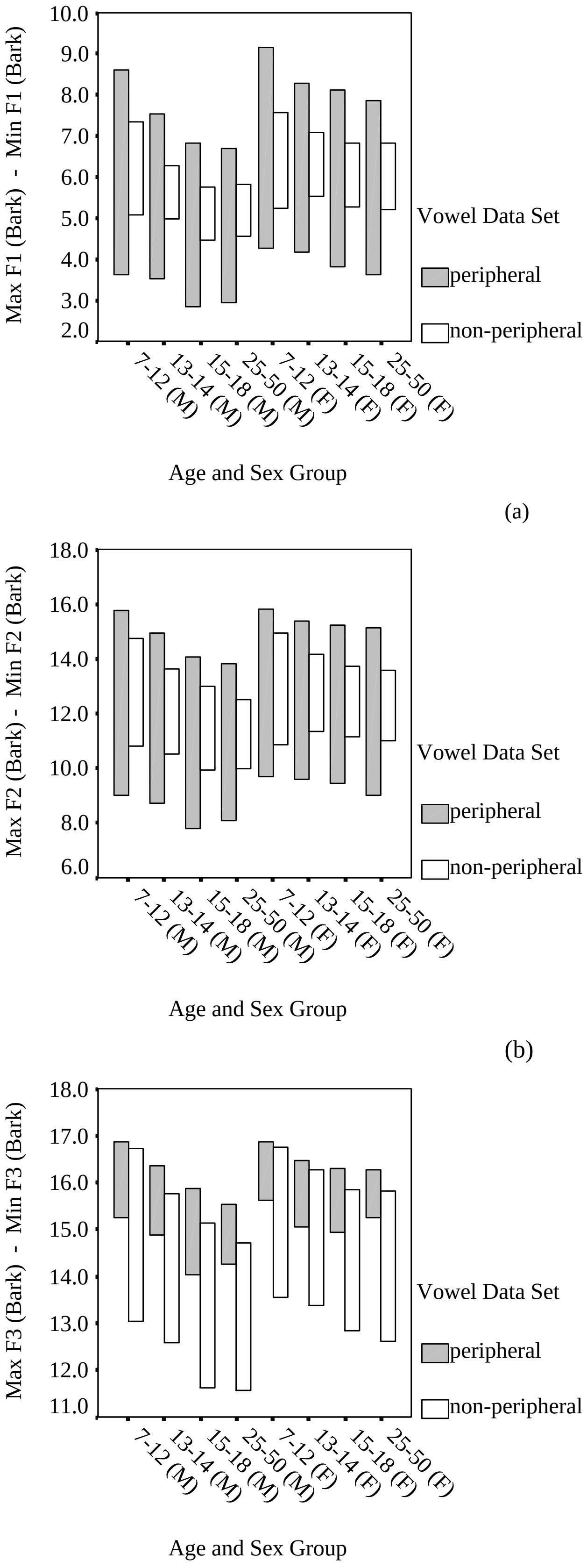

peripheral
non-peripheral
Z3-Z0 (Bark)
13.50
13.00
12.50
14.00
14.50
15.00
15.50
16.00
Z3 (Bark)
Group
○ 7-12M
● 7-12F
△ 13-14M
▲ 13-14F
▽ 15-18M
▼ 15-18F
▷ 25-50M
▶ 25-50F

FIG. 9


Max F1 (Bark) - Min F1 (Bark)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
Vowel Data Set
peripheral
non-peripheral
7-12 (M)
13-14 (M)
15-18 (M)
25-50 (M)
7-12 (F)
13-14 (F)
15-18 (F)
25-50 (F)
Age and Sex Group
Max F2 (Bark) - Min F2 (Bark)
18.0
16.0
14.0
12.0
10.0
8.0
6.0
Vowel Data Set
peripheral
non-peripheral
7-12 (M)
13-14 (M)
15-18 (M)
25-50 (M)
7-12 (F)
13-14 (F)
15-18 (F)
25-50 (F)
Age and Sex Group
Max F3 (Bark) - Min F3 (Bark)
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
Vowel Data Set
peripheral
non-peripheral
7-12 (M)
13-14 (M)
15-18 (M)
25-50 (M)
7-12 (F)
13-14 (F)
15-18 (F)
25-50 (F)
Age and Sex Group

(a)

(b)

(c)

FIG. 10

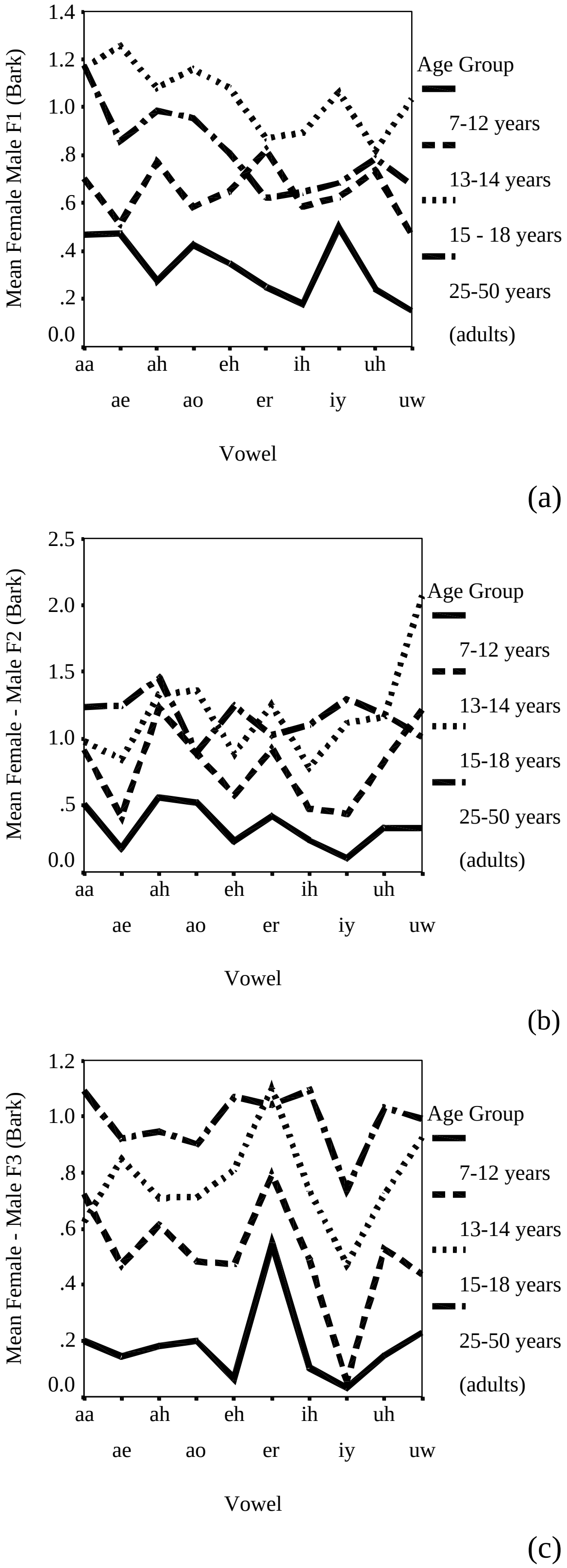

Mean Female Male F1 (Bark)
1.4
1.2
1.0
.8
.6
.4
.2
0.0
aa
ae
ah
ao
eh
er
ih
iy
uh
uw
Vowel
Age Group
7-12 years
13-14 years
15 - 18 years
25-50 years
(adults)
(a)
Mean Female - Male F2 (Bark)
2.5
2.0
1.5
1.0
.5
0.0
aa
ae
ah
ao
eh
er
ih
iy
uh
uw
Vowel
Age Group
7-12 years
13-14 years
15-18 years
25-50 years
(adults)
(b)
Mean Female - Male F3 (Bark)
1.2
1.0
.8
.6
.4
.2
0.0
aa
ae
ah
ao
eh
er
ih
iy
uh
uw
Vowel
Age Group
7-12 years
13-14 years
15-18 years
25-50 years
(adults)
(c)

FIG. 11