# Speaker normalization in speech perception

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Acoustic-phonetic analysis of speech, made practical by the advent of the speech spectrograph (Koenig, Dunn & Lacy, 1946), prompted a number of foundational questions regarding the perception of speech because spectrograms showed that speech is highly variable both within and between talkers. Among early researchers, Liberman et al. (1967) focussed on within-talker variation in the acoustic cues for stop place of articulation, while others focussed on between-talker variation in the acoustic cues for vowels. "Speaker normalization" refers to this second line of research centering on the fact that phonologically identical utterances show a great deal of acoustic variation across talkers, and that listeners are able to recognize words spoken by different talkers despite this variation. In defining speaker normalization in this way, we assume that phonological identity occurs when utterances are identified by listeners as instances of the same linguistic object (word or phoneme). For example, the word "cat" spoken by a man and a woman might be identified as "cat" by listeners though spectrograms will show that the man and woman have quite different vowel formant frequencies (Figure 1).

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Figure 1. Spectrograms of a man and a woman saying "cat". The three lowest vowel formants (vocal tract resonant frequencies) are marked as F1, F2, and F3.

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The most dramatic demonstration of between-speaker acoustic vowel variation is the well-known study reported by Peterson and Barney (1952). Figure 2 shows their plot of the first two vowel formant frequencies (F1 and F2) of vowels produced by men, women and children. All of the vowels represented in the figure were correctly identified by listeners. This figure - one of the most frequently reprinted in all of phonetics - has prompted decades of research, and serves as a starting point for this contribution

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Figure 2. Scatter plot of first and second formant frequency values of American English vowels. From Peterson & Barney (1952).

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Speaker normalization research prompted by between-talker vowel formant variation seeks to explain how listeners can correctly identify vowels when the main acoustic cues for vowel identity (F1 and F2) are ambiguous.

## PERCEIVING VOWELS IN ISOLATED SYLLABLES.

*Formants in vowel perception.* The importance of vowels formants (resonant frequencies of the vocal tract) in cueing vowel sounds has been known for over a century. For example, Helmholtz (1885) synthesized vowel sounds with resonators having frequencies that matched the vowel formant frequencies. The role of vowel formants in vowel perception was also demonstrated by Fry et al. (1962) using a continuum of synthetic vowels.

A debate pitting “formant-based” theories of vowel perception, in which auditory preprocessing is assumed to code vowels in terms of formant frequencies, against “whole spectrum" theories of vowel perception, in which a neural spectrogram serves as input to perception, suggests that the perceptual importance of vowel formants may result from the fact that the resonant frequencies of the vocal tract are the primary determinants of the spectral shape of vowels (see Rosner & Pickering, 1994, pp. 152-156). What is clear though is that in numerous studies using multi-dimensional scaling to empirically discover the dimensions of perceptual vowel space (Mohr & Wang, 1968; Pols, et al., 1969; Shepard, 1972; Terbeek & Harshman, 1972; Fox, 1982, 1983; Rakerd & Verbrugge, 1985) the first two perceptual dimensions always correspond to the frequencies of F1 and F2. However, the perceptual value of F1 and F2 are modulated by other acoustic properties of vowels.

*Perceptual influence of F0*. Miller (1953) doubled the fundamental frequency of vocal fold vibration (F0) of two-formant vowels (from 120Hz to 240Hz) and found vowel category boundary shifts for most of the vowels of English. Fujisaki and Kawashima (1968) also studied the role of F0 in vowel perception and found F1 boundary shifts of 100Hz to 200Hz for F0 shifts of 200 Hz. Slawson (1968) estimated that an octave change in F0 produced a perceived change in F1 and F2 of about 10-12%.

Listeners are also strongly affected by mismatched F0. Lehiste & Metzger (1972) found lower vowel perception accuracy when they put children's high F0 with male vowel formants, and (to a lesser extent) when they put low male F0 with children's vowel formants. Gottfried & Chew (1986) found that listener vowel identification performance was less accurate when vowels were produced by a counter tenor at a much higher F0 than is typcial for a male voice.

Johnson (1990) found that the F0 effect was sensitive to mode of presentation. If tokens having different F0 were randomly mixed, so that listeners couldn't predict the upcoming F0 the F0 vowel boundary shift was observed, but when stimuli were presented blocked by F0 the boundary shift was substantially reduced.

*Perceptual influence of higher formants*. It has also been reported that the boundaries between vowel categories are sensitive to the frequencies of a vowel's higher formants formants (F3-F5), though this effect seems to be much weaker than that of F0. Fujisaki and Kawashimi (1968) demonstrated an F3 effect with 2 different vowel continua. An F3 shift of 1500 Hz produced a vowel category boundary shift of 200 Hz in the F1-F2 space for a /u/-/e/ continuum, but a boundary shift of only 50 Hz in an /o/-/a/ continuum. Slawson (1968) found very small effects of shifting F3 in six different vowel continua. Nearey (1989) found a small shift in the mid-point of the /ʊ/ vowel region (comparable to a boundary shift) when the frequencies of F3-F5 were raised by 30%, but this effect only occured for one of the two sets of stimuli tested. Johnson (1989) also found an F3 boundary shift, but attributed it to spectral integration (Chistovich,1979) of F2 and F3 because the F3 frequency manipulation only influenced the perception of front vowels (when F2 and F3 are within 3 Bark of each other) and not back vowels which have a larger frequency separation of F2 and F3. This gives higher formant perceptual "normalization" a different basis than is normally assumed (see the literature on effective F2', starting with Carlson et al., 1970, as summarized in Rosner and Pickering, 1994).

## FORMANT RATIO THEORIES

Potter & Steinberg (1950) stated that in vowel perception "a certain spatial pattern of stimulation on the basilar membrane may be identified as a given sound regardless of position along the membrane." This is the basic idea of formant ratio theories - vowels are relative patterns, not absolute formant frequencies. The importance of formants and the effects of F0 and F3 in vowel perception support the F-ratio approach.

Miller (1989) traced formant ratio theories of vowel normalization from Lloyd (1890a,b; 1891, 1892), noting that "statements of the formant-ratio theory appear in the literature every few years since Lloyd's work ... , and, interestingly, the authors usually seem to be unaware of prior descriptions of the notion" (p. 2115). An explanation for this may be that most F-ratio theories seem to be inspired by an analogy between vowels and musical chords. For example, Potter and Steinberg (1950) in discussing their idea that vowels are a pattern of stimulation on the basilar membrane drew the analogy. "Musical chords, for example, are identified in this manner. Thus, the ear can identify a chord as a major triad, irrespective of its pitch position." (p. 812). They proposed that principles of Gestalt psychology permit the constancy of a visual object regardless of the exact location of the image on the retina, and must also be at work in audition to permit the constancy of patterns of stimulation on the basilar membrane. Traunmüller (1981, 1984) also concluded that "perception of phonetic quality" can be "seen as a process of tonotopic Gestalt recognition" (1984; p. 49).

Sussman (1986; Sussman et al., 1997) suggested a neuronal circuit, the "combination-sensitive neuron" that could accomplish this. His vowel normalization and representation model is shown in Figure 3. Combination sensitive neurons combine information from two formants at the point labelled (1) in the graph and then from three formants at point (2). Circuits comparable to this have been found in the auditory systems of a number of species (see Sussman et al, 1997, for a listing with references)[1] . Though Sussman demured regarding "the specific arithmetic processing" to be implemented by combination sensitive neurons, in his simulations he used the natural log of the ratios F1/F*, F2/F*, F3/F* where F* is the geometric mean of all of the formants. Bladon, Henton & Pickering (1986) implemented a whole spectrum matching model of

[1] Sussman's figure leaves out the fact that central auditory cortex has a tonotopic organization, and thus supports absolute frequency coding as well as the relative coding provided by combination sensitive neurons.

vowel perception that shares something of the spirit of Potter and Steinberg's and Sussman's approach to the formant ratio hypothesis. Though Bladon et al. didn't propose a neural mechanism like Sussman's, they did demonstrate that one way to concieve of matching "spatial patterns of stimulation on the basilar membrane" is to calculate auditory vowel spectra and then slide the spectra from female talkers down into the range occupied by male talkers.

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Figure 3. Sussman's vowel normalization/representation model, making use of combination-sensitive neurons to code relations among formant frequencies. Formant ratio data for men, women and children are shown in the "vowel normalization fields".

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*Forms of the formant ratio hypothesis*. A number of analytical statements of formant ratio normalization have been given. This section briefly presents them with a focus on their similarities.

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| Peterson (1961) | log($F_n$)- log( $F_1$), n=2,3,4 |
| Sussman (1986) | log(Fn/F*), n=1,2,3, F*= (F1+F2+F3)/3 |
| Syrdal & Gopal (1986) | Bark(F1)-Bark(F0), Bark(F2)-Bark(F1), Bark(F3)-Bark(F2) |
| Miller (1989) | log(F1/SR), log(F2/F1), log(F3/F2) |

Table 1. Formulations of the formant ratio hypothesis.

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Note in comparing the formulations in Table 1 that log(x) - log(y) = log(x/y). Thus, Peterson and Miller have one dimension in common: log(F2/F1) = log(F2)-log(F1). Note also that the Bark scale is a non-linear scale similar to the log scale. Thus, Miller and Syrdal & Gopal have almost the same dimensions - one difference being that Syrdal and Gopal enter F0 directly, while Miller's formula reduces the influence of F0 fluctuation by using a "sensory reference" (SR) derived from the geometric mean of F0 over an interval of time. It is interesting that F3 and F0 have equal status in Syrdal & Gopal (1986) and Miller (1989), and that F0 is not included in the formant ratios of Peterson (1961) or Sussman (1986). This seems to run counter to the fact that the effect of F0 on perception is much larger and more consistent than the effect of F3 and the higher formants. In fact, there are a number of other perceptual effects that suggest that formant ratio theories are inadequate.

## FROM AUDITORY GESTALTS TO VOCAL TRACT ACTIONS.

*Beyond formants*. As important as formant frequencies are in vowel perception, it has also been demonstrated that listeners use "secondary" cues. Lehiste & Peterson (1961) showed that American English vowels differ in terms of duration and formant frequency movement trajectories -- tense vowels are longer than lax vowels, low vowels are longer than high vowels, and formant trajectories differ for vowels that are otherwise close in the F1/F2 space. For example, /e/ is more narrowly transcribed [eɪ] while /ɛ/ tends more to [ɛə]. The perceptual importance of these acoustic characteristics of American English vowels has been demonstrated in studies on the perception of synthetic steady-state vowels and on the perception of "silent-center" vowels. Lehiste & Metzger (1973) showed that listeners are not very successful in correctly identifing fixed duration vowels synthesized with steady-state formant frequencies (51% correct with 10 vowel categories). They were much better at identifying the original isolated vowel recordings - though with mixed lists containing tokens from men, women, and children the identification rate even in this task was quite low (79% correct) (see also Ainsworth, 1972). Assman and Nearey (1986) spliced small chunks out of vowels near the beginning of the vowel segment (the "nucleus") and near the end (the "glide") and found that correct identification was higher when the chunks were played in the order nucleus/glide than when either chunk was presented alone or when they were played in the order glide/nucleus. Hillenbrand and Nearey (1999) presented an extensive study of vowel identification that confirms the conclusions of these earlier studies. Flat-formant vowels (vowels synthesized with only steady-state formant frequencies, but having the duration of the original utterance) were correctly identified 74% of the time, while vowels synthesized with the original formant frequency trajectories were correctly identified 89% of the time.

The point in citing these studies is to counter the tendency (sometimes stated explicitly) to think of formant ratio vowel representations as points in a normalized vowel space. Miller's (1989) description of vowels as trajectories through normalized space is much more in keeping with the data reviewed in this section. However, even with these richer vowel representations, formant ratio theories fail to account for perceptual speaker normalization.

*Whispered vowels*. Rosen & Pickering (1994) note that formant ratio models of vowel perception that necessarily include F0 (e.g. Miller, 1989; Syrdal and Gopal, 1986; and Traunmüller, 1981) have no explanation for the fact that listeners can identify whispered vowels. It should be noted, though, that whispered vowels are not identified as accurately as normally phonated vowels.. Eklund and Traunmüller (1997) found error rates of 4.5% for voiced vowels and 12% for whispered vowels. In whisper the vocal tract resonances (particularly F1) shift up in frequency with the glottis open (introducing tracheal resonances and zeros), and x-ray studies show that vowel articulations also change in whispered speech (Sovijärvi, 1938). So it is not surprizing that whispered vowels are harder to identify, but the fact remains that models that require F0 in the representation of vowels fail to account for the perception of whispered vowels.

*Beyond vowels*. Though the focus of speaker normalization research has been on vowel perception, listeners are also sensitive to talker differences in the perception of consonants and prosody.  Schwartz(1968) found in an acoustic study that fricatives produced by men and women have, on average, different spectral shapes (fricatives produced by women had slightly higher spectral center of gravity), and May (1976) found that when a continuum from [s] to [ʃ] was spliced to [ɑ] produced by a male or a female voice, the [s]-[ʃ] boundary was at a higher spectral center of gravity for the female voice.  This was taken to mean that listeners "normalized" the fricative based on the contextual information provided by the vowel. This finding has been replicated a number of times (e.g. Mann and Repp, 1980; Johnson, 1991; Strand and Johnson, 1996).

Leather (1983) found speaker normalization effects with Mandarin Chinese tones. The pitch range of a context utterance influenced the perception of test tones spanning a range of F0 values.  This type of tone normalization effect has also been reported by Fox and Qi (1990) and by Moore (1994).

*Scatter reduction*.  Normalization algorithms such as formant ratio recoding are evaluated according to how well they reduce within-category scatter and between-category vowel overlap. The goal is to devise a cognitively plausible algorithm that is able to separate the overlapping clusters of vowels in the Peterson & Barney (1952) figure, for example, and so classify the vowels about as accurately as Peterson & Barney's listeners did. When it comes to scatter reduction, though, no algorithm has been shown to work better than simple statistical standarization of formant values (Labonov, 1971; Disner, 1980; Nearey, 1978).[2] The problem with this kind of method, from the perspective of cognitive plausibility is that in order to recode a talker's formants into speaker-specific z-scores ($z = (x \square \bar{x}) / sd$) the algorithm has to have a full listing of formant frequency measurements of vowels produced by the talker. It does not seem plausible to suppose that listeners could have enough information from an unfamiliar talker to be able to perform this kind of normalization.

Despite this, most of the practically useful vowel normalization algorithms require that summary statistics be derived over a full set of vowels for each talker. As we have seen, Lobanov's (1971) method requires the mean and standard deviation of F1 and F2. Nearey's (1978) constant log interval normalization uses the mean of the log values of the talkers' F1 and F2. Gerstman's (1968) range normalization technique (which is less successful than formant standardization or log interval coding) requires that the minimum and maximum values of F1 and F2 be found. Bladon, Henton and Pickering (1984) used a single value to normalize vowels - a boolean to indicate whether the talker is male or female. If the vowel was produced by a woman the auditory spectrum was shifted down by about 1 Bark. The specta of vowels produced by men were not shifted. In this approach 1 Bark is about the magnitude of the average frequency difference between the formants of vowels produced by men and of those produced by women (see figures 5 and 6 below).

The main point of these observations is to note that it has proven useful in the practical quantitative normalization of vowel formant data to express formant frequencies relative to a representation of the talker. In Lobanov's method the talker representation has four dimensions $m_{F1}$, $m_{F2}$, $s_{F1}$, and $s_{F2}$. In Nearey's most successful version of the constant log interval method

[2] Hindle (1978) describes a six parameter regression model attributed to Sankoff, Shorrock & McKay which reduces scatter to such an extent that known sociolinguistic variability is removed from the normalized vowel space.

the speaker is represented as $m_{\log F1}$ and $m_{\log F2}$. For Bladon et al. the boolean shift factor is a kind of talker representation - men are represented as 0 and women are represented as 1. In considering these normalization algorithms as possible models of human perceptual speaker normalization, it is interesting to note that a perceptual frame of reference perhaps analogous to these statistical acoustic representations is used by listeners. We turn now to some evidence supporting this view.

*Context influences perception*. One of the cleverest and most influential studies of vowel perception was the one reported by Ladefoged and Broadbent (1957). Like Peterson & Barney's (1952) study, Ladefoged & Broadbent's results have had a lasting impact on the theory of speech perception. They found that vowels judged in the context of a precursor carrier phrase with the vowel formant frequencies shifted up were identified differently than when the precursor phrase had relatively low vowel formants. In effect, the test vowels were identified as if the precursor phrase provided a coordinate system within which to judge them. This "extrinsic" context effect has been demonstrated in numerous subsequent studies (Ainsworth, 1974; Nearey, 1978, 1989; Dechovitz, 1977). Remez et al. (1987) found that the context formant range effect also occurs in the perception of sinewave analogs of speech. Johnson (1990) found a variant of the effect in which the F0 range of the carrier phrase was varied instead of the vowel formant frequency range. The effect of carrier phrase F0 range was comparable to the vowel formant frequency range effect noted by Ladefoged and Broadbent.

The impact of context on vowel perception suggests that listeners use a cognitive "frame of reference" that is in some sense a representation of the talker who produced the speech. If something like this actually happens in speech perception, it would be reasonable to expect to find evidence that listeners take a little time to adapt to a new talker exhibit processing difficulties such as misperceptions and/or slowed responses before talker adaptation has been completed. These expectations have been born out in a number of studies over the years.

*Talker normalization is an active process*. Creelman (1957) found that word recognition accuracy in noise decreases when the identity of the talker is unpredictable from trial to trial. In this study and many later ones, talker identity was kept predictable by presenting stimuli in "single-talker" lists, while in the unpredictable talker condition the stimuli were presented in "mixed-talker" lists. Summerfield & Haggard (1975) found that word recognition reaction times were slower in mixed-talker lists than in single-talker lists. Verbrugge et al. (1976) found that vowel identification was more accurate in single-talker lists (9.5% errors) than in mixed-talker lists (17% errors). Mullennix, et al. (1989) tested word recognition speed and accuracy in mixed and single-talker lists and also investigated interactions with word frequency and lexical density. They suggested that speaker adaptation is an active process and that talker voice information is not automatically "removed" from the speech signal by a normalizing recoding of the signal otherwise the talker variability manipulation wouldn't have had an effect.

Kakehi (1992) described experiments done earlier by Kato & Kakehi (1988) that investigated listener adaptation to talker voice. They found a very interesting effect of adaptation (as indicated by increased syllable recognition accuracy in noise) over the course of five successive stimuli. Accuracy increased monotonically from 70% correct on the first stimulus produced by a talker, to 76% correct on the fifth stimulus. After the fifth stimulus, no further increase in recognition accuracy was observed. This study calibrates the amount of information needed to adapt to a new talker for isolated nonsense syllables (letter names basically). Nusbaum & Morin (1992) used a speeded phoneme monitoring task to evaluate the effect of talker uncertainty in a mixed talker list. They found that listeners were slower to report the presence of target syllables in mixed-talker lists. This was taken to indicate that speaker normalization is an active adaptation process that demands cognitive resources.

*Talker normalization is subject to expecations*. Magnuson and Nusbaum (1994) compared “1-voice” instructions with “2-voice” instructions in a mixed-talker monitoring task where the two synthetic voices were only slightly different in F0. Listeners were told either that the tokens were produced by two talkers or one. In the 2-voice instruction condition, they found the typical advantage for blocked-talker presentation versus the mixed-talker presentation, but this effect disappeared in the 1-voice instruction condition. A perceptual effect of instructions was also found in another study by Johnson, Strand and D’Imperio (1999). In one experiment, listeners were presented synthetic tokens on a “hood” [hʊd]-”HUD” [hʌd] continuum with an androgynous voice. One group of listeners was told that the talker was female and the other group was told that the talker was male. The category boundaries were different as a function of instructions in the same direction as found when F0 or visual gender was used to cue talker differences.

Eklund and Traunmüller (1997) found evidence of a connection between talker perception and vowel perception, this time in a study of whispered speech. When listeners misidentified the sex of the talker their vowel identification error rate was 25%, but when they correctly identified the sex of the speaker the vowel error rate was only 5%. This suggests that talker perception and vowel perception are interconnected with each other, as the studies using experimenter-suggested talker expectations seems to show.

*Audio-visual interactions in normalization.* Several studies have shown that listeners process speech differently in audio-visual presentation depending on the visual gender of the talker (Walker et al., 1995; Strand and Johnson, 1996; Schwippert and Benoit, 1997; Johnson et al. 1999). Auditory/visual perceptual integration is more likely to occur when the gender of the visually presented face matches the gender of the auditorily presented word. Strand and Johnson, and Johnson et al. also found that fricative and vowel identification boundaries can be shifted by visual gender in much the way that they can be shifted by F0, or other auditory cues for talker gender. Walker et al. found a very interesting interaction between auditory/visual integration and listener familiarity with the talker.

Taken together, these phenomena suggest that listeners perceive speech relative to an internal representation of the person talking. The earliest and most straightforward proposal was that the "talker" frame of reference (or perceptual coordinate system) for speech perception is the vocal tract of the talker.

## VOCAL TRACT NORMALIZATION

Whereas formant ratio theories view normalization as a function of the auditory gestalt encoding of vowels, vocal tract normalization theories consider that listeners perceptually evaluate vowels on a talker-specific coordinate system - most simply, by reference to the perceived length of the talker's vocal tract. The normalization mechanism in this approach is thus a kind of predictive analysis-by-synthesis mental model of the vocal tract.

Here is Martin Joos' (1948) account of vocal tract normalization.

> "On first meeting a person, the listener hears a few vowel phones, and on the basis of this small but apparently sufficient evidence he swiftly constructs a fairly complete vowel pattern to serve as a background (coordinate system) upon which he correctly locates new phones as fast as he hears them. ... On first

> meeting a person, one hears him say “How do you do?”. The very first vowel phone heard is a sample of the noise this speaker makes when his articulation is (in my dialect) low central; the last one is a sample of the noise he makes with his highest and backest articulation; and in the middle (spelling “y”) there is a sample of sound belonging to palatal articulation, offering evidence about his higher and fronter vowels. Now these samples of sound as sound are already sufficient to establish the acoustic vowel pattern: the pattern’s corners are now located, and the other phones can be assumed to be spaced relative to them as they generally are spaced in this dialect.” (p. 61)

The fact that perceived vowel quality is influenced by the formant frequencies of context vowels (Ladefoged & Broadbent, 1957) suggests that something like Joos’ “coordinate system” is involved in vowel perception. And evidence that speaker normalization is an active process open to visual information about the talker, and other information that can be used to specify the talker’s vocal tract size, fits with the idea that listeners are constructing a perceptual frame of reference. Additionally, the analysis-by-synthesis mechanism is general enough to be extended to account for perceptual normalization in the perception of consonants and tones.

Besides extrinsic cues such as the range of formant frequency values in the immediately preceding speech context, some vowel internal cues carry information about the talker’s vocal tract. For example, though F0 is not causally linked to vocal tract length (as Nearey, 1989, memorably noted with his imitations of the cartoon character Popeye whose vocal tract was long though his vocal pitch was high, and the American television personality Julia Child whose low pitch voice belied her short vocal tract), there is a presumptive correlational relationship so that

F0 may serve as a rough vocal tract length cue which could play a role in establishing the vocal tract normalization “coordinate system”. The frequency of the third formant is causally linked to vocal tract length and was used explicitly by Nordström and Lindblom (1975) in a vowel normalization algorithm.  They first calculated the length of the vocal tract for a particular speaker from the frequency of F3 in low vowels and then rescaled the other vowel formants produced by this speaker to a standard speaker-independent vocal tract length.

*How much context is needed?*  Verbrugge et al. (1976) noted that single syllables presented in mixed-talker lists are identified very accurately (95% correct in Peterson & Barney’s, 1952, study), and conclude that “there is clearly a great deal of information within a single syllable which specifies the identity of its vowel nucleus” (p. 203). They conducted experiments comparing vowel identification in a mixed-talker list, with or without a set of three context syllables.  In each condition, there was a slight but statistically unreliable increase in vowel identification accuracy with the addition of precursor vowels - whether they were point vowels or not. However, they also noted that vowel identification performance in a single-talker list was much better than in a mixed-talker list. This suggests that limited context like a set of three nonsense vowel sounds does not provide much talker information beyond that already available in an isolated syllable and that this initial short-term adaptation to talker is different from vowel identification performance based on more extended familiarity with the talker.

This difference in performance for stimuli presented with point vowels as the immediate context in a vowel identification experiment and stimuli presented in a single-talker list, is not predicted by the vocal tract normalization theory.  However, the different patterns of results in Verbrugge et al. (1976) and Kato and Kahehi (1988) casts doubt on any conclusions we might draw from either study.  Further exploration of the time-course of talker adaptation is needed.

*Uniform scaling, nonuniform scaling, and vocal tract perception*. Nordström and Lindblom's (1975) uniform scaling approach to vowel normalization used a single scale factor (hence "uniform" scaling) to shift vowel formant measurements into a talker-independent coordinate system.[3] For the F-scaling factor they used the ratio ($k$) of the speaker's vocal tract length, to a reference vocal tract length ($l_{AV}/l_{ref}$). They estimated $l_{AV}$ from the average F3 value found in low vowels, and Fant (1975) showed that k can be estimated as an F3 ratio:

$$k = F3_{AV}/F3_{ref} \qquad (1)$$

Though uniform scaling reduces talker differences quite a bit, it had been recognized for some time (Fant, 1966) that no uniform scaling method can capture systematic, cross-linguistic patterns that have been observed in male/female vowel formant differences. In dealing with these male/female differences, Fant (1966) used separate scale factors for the F1, F2, and F3 of each vowel in order to relate male and female measurements. This gives 30 scale factors per talker for a system with ten vowels.

The non-uniformity of male/female formant differences means that a normalization routine like Nearey's one parameter version of the constant log interval method, or Bladon, Henton and Pickering's one parameter spectral shift method are unlikely to succeed in equating male and female vowels. Both of these succeed better than Fant's uniform scaling of formant values in Hz because their nonlinear scales absorb some variation due to the fact that male and female vowel formants differ as a function of formant frequency - approximating each other somewhat closely at low formant frequencies and differing quite a lot at higher frequencies. Nonetheless, uniform normalization, based on the implicit assumption that vocal tract length is the only difference between men and women, neglects the effects other important differences in

[3] Actually, as with many other studies, they chose a "standard male" vowel space as the reference.

vocal tract geometry.  For example, men tend to have a proportionally longer pharynx than women, and thus lower back-cavity resonance frequencies.

Nonuniform normalization, utilizing different scale factors for different formants (including multiparameter models like Lobanov, 1971, and Nearey, 1978) provides more complex representations of the talker --- reflecting presumably, for the moment, differences in vocal tract geometry beyond vocal tract length.  Model studies of typical vocal tract differences between men and women have attempted to derive Fant's (1966) nonuniform scaling factors from anatomical differences between men and women (Nordström, 1977; Goldstein, 1980; Traunmüller, 1984).

Rather than simply to rescale formant frequencies based on an estimate of vocal tract length, or to characterize the talker in terms of acoustic formant scale factors, McGowan (1997, McGowan & Cushing, 1999) attempted to recover a detailed characterization of vocal tract geometry from the acoustic signal. One difficulty with this more literal approach to vocal tract normalization is that indeterminacies in the extraction of acoustic parameters are magnified during vocal tract simulation. This coupled with a degree of vocal tract underspecification (such that virtually identical acoustic values can be produced by substantially different vocal tracts, Atal, et al. 1978) puts speech gesture recovery, as a practical normalization strategy, out of reach at this time. Whether listeners veridically recover the talker's vocal tract for use in perceptual speaker normalization is another question.

The presence of individual differences in speech production (Johnson, et al., 1993) also complicates matters for vocal tract normalization. Though normalization research has usually focussed on male/female differences in vocal tract size and shape, vocal tracts -- even within genders -- come in lots of different sizes and shapes. Johnson et al.'s results suggest that talkers apparently adopt different (possibly arbitrarily different) articulatory strategies to produce the "same" sounds. Thus, accurate recovery of the talker's articulatory gestures would not completely succeed in "normalizing" speech.

## TALKERS OR VOCAL TRACTS?

We turn now to a discussion of talkers, starting with consideration of the articulatory origins of gender differences in speech, followed by a discussion of the role of the perceived identity of the talker in speech perception. As noted above, talkers may differ from each other at the level of their articulatory habits of speech. This in itself would suggest that perception may not be able to depend on vocal tract normalization to "remove" talker differences by removing vocal tract differences. However, because so much of the normalization literature focusses on the differences between men's and women's speech, we will start by asking a prickly question.

*Do men's and women's voices differ only by anatomy?* Vocal tract normalization theory assumes that speakers differ from each other in vocal tract anatomy, but that when this source of difference is factored out all speakers of a language have the same phonetic targets. Traunmüller (1984) presented results supporting this idea from simulations of differences between male and female formant frequencies. In his simulations, Traunmüller modeled male/female differences in pharynx length and resting tongue position (assuming that the decent of the larynx lowers the resting position of the tongue). Possible gender difference in resting tongue position had not been considered in previous studies (Nordström, 1977; Goldstein, 1980) and Traunmüller offered no data to support the crucial assumption. Nonetheless, his simulated male/female formant ratios closely match the average ratios reported by Fant (1966, 1975). Rosner and Pickering (1994) accepted Traunmüller's conclusion that "it is not necessary to postulate sex-specific vowel articulations in order to explain the [non-uniform formant scaling] data" (Traunmüller, 1984, p. 55).

However, it has been noted by several researchers (Meditch, 1975; Henton, 1992; Chan, 1997) that men and women differ from each other at most levels of linguistic structure. Gender differences in speech production patterns have also been frequently noted (e.g. Byrd, 1994). Because dialect variation is often cued by phonetic differences, it seems reasonable to expect that male and female phonological "dialects" may exist in most languages.

Some researchers posit an ethological basis for some male/female differences (Ohala, 1984), while others suggest that male/female differences may be an aid to communication (Diehl et al. 1996). Whatever the cause for behavioral gender differences in speech, there is reason to believe that anatomical differences are not the exclusive source of the differences between men and women's vowel spaces. The evidence suggests that talkers differ from each other in other ways that can not be predicted from vocal tract anatomy differences alone, and thus that the "coordinate system" used by listeners in speech perception is probably related to talker differences that extend beyond vocal tract differences.

*Acquisition of gender differences*. Data from studies of gender differentiation in children show that listeners can correctly identify the sex of prebubescent boys and girls on the basis of short recorded speech samples. Results from these studies are summarized in Table 2. These data have been taken to suggest that boys and girls learn to speak differently before their vocal tract geometries diverge at puberty (but see below). Acoustic analysis of the stimuli used in the Sach et al., Bennett and Weinburg, and Perry et al. studies indicate that listeners' responses were based primarily on the frequencies of the vowel formants, particularly F2, rather than F0, the most salient cue for adult gender.

Table 2. Results of studies in which listeners were asked to identify the sex of children on the basis of short recorded speech samples. The data listed under males and females are the percent correct gender identification scores for boys and girls.

| | % correct | | | |
|---|---|---|---|---|
| | boys | girls | age | speech segment duration |
| Sachs, et al., 1973. | 86% | 75% | 4-14 years | 3 seconds |
| Meditch, 1975 | 85% | 74% | 3-5 years | 2 minutes |
| Bennett & Weinburg, 1979a | | | | |
| phonated vowels | 68% | 63% | | 1 second |
| whispered vowels | 67% | 65% | 6-7 years | |
| sentence (monotone) | 81% | 63% | | 3 seconds |
| sentence (normal) | 71% | 69% | | |
| Ingrisano et al. (1980) | 70% | | 4.5 years | 3 seconds |
| Perry et al. (2001) | | | | |
| blocked by age | 67% | 62% | 4 years | CVC syllables |
| | 74% | 56% | 8 years | |
| | 82% | 56% | 12 years | |
| | 99% | 95% | 16 years | |

Figure 4 shows children's average vowel formant data from the extensive study by Lee, et al. (1999), together with data from 4, 8, 12, and 16 year-olds from Perry et al. (2001). Data not shown in the figure for 8 year-olds from Bennett (1981), for 11 year-olds from White (1999), for 11, 12, and 13 year-olds and adults from Eguchi & Hirsh (1969), and for 9 year-olds and adults from Most et al. (2000) show the same trends. Boys and girls show small, consistent (and when tested, significant) differences in their vowel formant frequencies well before the onset of puberty. After the age of about 13 years boys and girls begin to differ more substantially.

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Figure 4. Average frequencies of the second vowel formant (in Bark), for children ranging from 5 to 17 years old. Data plotted in panel (a) are from Lee et al. (1999) and data plotted in panel (b) are from Perry et al. (2001). Filled symbols and solid lines plot the male formant frequencies and open symbols and dashed lines plot the female formant frequencies.

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Bennett (1981, p. 238) found a relationship between measures of gross body size and children's formant frequencies which suggested that "the larger overall size of male children also results in a larger vocal tract." Perry et al. (2001) quantified the extent to which gender differences in children's vowel formants can be predicted from age and body size. In their regression analysis, age and body size measurements account for most of the variance in children's measured formant frequencies (82-87% of the variance), but gender as a separate predictive factor also accounts for a significant proportion of the variance of each formant. Gender accounted for 5% of additional variance of F1 and F3 and 9% of additional F2 variance. It is interesting that the largest gender effect was observed for F2 - the formant that has the largest range of speaker controlable variation. The authors of all of these studies on sex differentiation in children's speech conclude much as White (1999, p. 579) did that, "males and females may well adopt gender-specific articulatory behaviors from childhood to further enhance sex distinctions."

*Cross-linguistic gender differences.* Bladon, Henton and Pickering (1984) compared the amount of spectral shift needed to normalize male and female spectra for speakers of different languages. They found that the difference between men and women varied from language to language. Cross-linguistic variation in how male and female talkers differ from each other might indicate that cultural factors are involved in defining and shaping male or female speech - and thus that anatomy does not completely determine the vowel formant frequencies.

Figure 5 shows the gender difference for F1-3 for 26 different groups of speakers. This dataset, which was drawn from a number of published reports, includes data for many unrelated languages, as opposed to the generally western-language bias of previous cross-linguistic comparisons. For Figure 5, the male-female formant frequency differences for five vowels [i,e,a,o,u] in each language were averaged. If the language has fewer than five vowel qualities the average was over the 3 or 4 vowels in the language. Only long vowels were sampled if the language distinguishes between long and short vowels. The languages were sorted from smallest gender difference for F2 (Danish) to largest F2 difference (Russian), and as the figure shows, the first and third formants show the same general trend as F2, though the ordering would somewhat be different if we sorted F1 or F3 differences.

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Figure 5. The difference between men's and women's average formant frequencies for 26 groups of speakers. F1 is plotted with a crossed open box, F2 is plotted with a filled circle, and F3 is plotted with an open triangle.

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As the figure shows, men and women have quite similar vowel formants in some languages like Danish with less than 1/2 of a Bark difference between men and women for F1, F2 and F3, while other languages show formant frequency differences that are more than double this like Russian.

Figure 6 shows the formant frequency differences between men and women as a function of the women's formant frequencies for the raw data that went into Figure 5. (The F by DF space was suggested by Simpson, 2001.) The horizontal axis shows the vowel formant frequency for women's vowels, and the vertical axis shows the formant frequency difference between men and women. Three clusters of points, for F1, F2 and F3, are shown against Traunmüller's (1984) model predictions plotted with filled symbols. Traunmüller's gender differences predictions match the average cross-linguistic pattern for this sample of 26 studies quite well, indicating that vocal tract geometry differences may account for the general pattern of the data, but the data are not tightly clustered around the predicted values. Overall only 30% of the variance is accounted for by the vocal tract differences model.

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Figure 6. The F by DF space for 26 groups of male and female adult speakers. Male-female formant differences as a function of female formant frequency. F1 values from the cross-linguistic data set are plotted with plus signs, F2 data are plotted with x, and F3 is plotted with diamonds. The solid symbols plot the predicted F by DF relationships from Traunmüller's (1984) simulations of male-female "anatomy-only" formant differences. The solid regression lines are fit to Traunmüller's predictions, and the dashed

regression lines fit the cross-linguistic data.

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Traunmüller's (1984) model of male-female vocal tract differences was based on anatomy studies of particular speakers, so the unexplained variance in Figure 6 needs to be partialled between variance due to specific talker's vocal tract (vs. average male or female geometry) and remaining gender differences in habits of articulation attributable to gender "dialect" differences specific to particular speech communities.

These explorations into gender differences in vowel production by children and across cultures suggest that talkers choose different styles of speaking as social, dialectal gender markers. Thus, a speaker normalization that removes vocal tract differences will fail to account for the linguistic categorical similarity of vowels that are different due to different habits of articulation (for individuals or gender "dialect" differences). Numerous studies indicate that talker-specific characteristics interact with spoken language processing. What is more, if listeners were not able to sense the aspects of phonetic production that vary due to the idiosyncrasies of talkers, then they would be unable to control their own expression of these free subphonemic contrasts.

*Familiarity with the talker affects recognition*. Interactions between talker identity and spoken language processing have been found in studies where prior familiarity with the talker influences processing. For example, Lightfoot (1989) trained listeners to recognize talkers and found that listeners remembered words presented in a serial recall list better when they were spoken in a familiar voice. Walker et al. (1995) took advantage of listener's natural familiarity with talkers (by using colleagues as talkers and listeners) and found that audio/visual integration in the "McGurk effect" was modulated by familiarity. When the face and voice came from different talkers, the audio and visual streams were not integrated for listeners who were familiar with the talkers. Nygaard and Pisoni (1998) using a talker learning paradigm like Lightfoot's found that learning a talker from sentences does not lead to better word recognition performance, but learning a talker from words leads to better word recognition performance and learning talkers from sentences leads to better sentence processing performance. This is a quite important finding because it suggests that the talker information being learned is not simply related to static vocal tract geometry, but instead must have something to do with how people say things in the particular instances heard – reflecting their habits of articulation.

*Sociophonetic effects in spoken language processing*. We saw in a section above that listener expectations can influence speech perception. We discussed that data in the section leading up to vocal tract normalization theory because it could be assumed that the effect of listener expectations is limited to relating the incoming speech to a particular vocal tract represenation. However, further evidence suggests that listener's expectations are related to social stereotypes rather than veridical vocal tract parameters.  In socio-phonetics it has been demonstrated through "matched guise" experiments that listeners are likely to attribute personality traits to people on the basis of their speech patterns. Recently, this approach has been extended to speech perception. Rubin (1992) found that speech intelligibility is reduced when American college-age listeners associate a voice with an Asian looking face. He presented the same recorded lectures with a picture of an Asian lecturer or a Caucasian lecturer, and found lower listening comprehension scores for listeners who saw the Asian lecturer.  Niedzielski (1997) found that the perceived nationality of a talker ("Canadian" or "American") influenced vowel perception.  She used a vowel matching procedure and told one group of listeners that the speaker was from Ontario, Canada and another group of listeners that the speaker was a native of

Detroit. In matching synthetic vowel tokens to naturally produced words, listeners choose vowel tokens that exhibited Canadian raising (the pronunciation of the English /aʊ/ diphthong as [ʌʊ]) if the talker was identified as a “Canadian”, but choose nonraised variants as vowel matches if the talker was identified as an “American”. What is especially telling about this result is that the speaker (a Detroit native) actually pronounced the words with Canadian raising, so these Detroit listeners ended up giving non-veridical answers in their matching responses to the “American” speaker.  In both of these studies, listeners’ socially-based expectations, regarding the talker’s group membership, influenced perception. Similar perceptual effects for socially-based expectations have also been observed in a role for gender in speech perception.

Strand (2000) found that gender stereotypicality influences auditory word recognition. She measured stereotypicality implicitly as the convergence of a multidimensional scaling analysis of the perceptual space for a group of talkers and a speeded gender classification task. The main result of Strand’s study is that auditory word naming was slower when the talker was a nonstereotypical male or female than when the talker was stereotypical.  Interestingly, the male “nonstereotypical” talker in this study had an unusually low fundamental frequency - so he was nonstereotypical by sounding somewhat “hypermale” rather than being a bit androgynous.

*Exemplar effects in word recognition*. Acoustic-phonetic details of utterances seem to be a part of the listener’s long term representation of speech.  This has been demonstrated in tests of recognition memory and more importantly in tests of auditory word recognition. Palmeri et al. (1993) using a continuous recognition memory task, found that spoken words were more accurately recognized as “old” when they were repeated in the same voice than if they were repeated by a different talker. Church and Schacter (1994) found effects of voice, affect, and pitch range in an implicit memory task. Word recognition performance was better when primes (presented in a study list) and targets (presented in a test list) matched on these dimensions. These findings indicate that fine phonetic details, such as those associated with talker differences, remain as a part of the listener's memory of words. Goldinger (1996, 1997) also tested for the influence of talker-specific information in recognition memory for words. He found that talker repetition affected recognition memory with a one day gap between study and test. More significantly he also found repetition effects in perceptual identification. Previously heard items were identified more accurately even at the longest interval tested - one week between exposure and test. The long retention of talker-specific acoustic detail in this study is not consistent with abstractionist models of speaker normalization like the F-ratio and vocal tract normalization theories but is support for episodic/exemplar coding models.

**TALKER NORMALIZATION**.

Exemplar-based memory models (a common approach to the study of categorization and memory in cognitive psychology) offers an advance over vocal tract normalization theory in accounting for speaker normalization in speech perception. In this approach, cognitive *categories* are represented as collections of the stored cognitive representations of experienced *instances* of the category, rather than as normalized abstract representations from which category-internal structure has been removed (Hintzman, 1986; Nosofsky, 1986, 1988; Kruschke (1992).

Instance-based, or exemplar-based models exhibit behavior that is very much like the generalization behavior of prototype theories (Hintzman, 1986). The main difference is that generalization in an instance-based system takes place during retrieval/activation of the category rather than during category storage/creation. Thus, on-line category adaptation, such as talker adaptation, is possible.

In exemplar-based “speaker normalization” the frame of reference, or coordinate system, is a set of “experienced” exemplars rather than a vocal tract (Johnson, 1997a,b). Rather than warp the input signal to match a fixed internal template, the internal representation adapts according to the “perceived identity of the talker” (Johnson, 1990), as exemplars appropriate for the talker are activated and inappropriate exemplars are deactivated forming a base activation rate (Nosofsky, 1988). In this system talker cues of all kinds can be involved in tuning the activated set of exemplars - visual representation, prior expectations, recognition of a specific known voice, and acoustic cues (F0 as a gender cue, but also formant range).

Additionally, exemplar models offer an adaptation mechanism that accounts for all kinds of variation that influences listeners including dialect variation, and the impact of unusual acoustic environments such as reverberation. Some surprising findings in the literature can be explained when perception is considered to be based on an exemplar-based memory system. For example, Nygaard and Pisoni’s (1998) odd finding that talker learning is mode specific - talker representations learned from isolated words were not helpful to listeners in a sentence processing task. Eklund and Traunmüller’s (1995) finding that talker and word misperceptions are correlated - listeners were more likely to misperceive the message if the gender of the talker had been misperceived. Strand’s (2000) finding that nonstereotypcial voices were processed more slowly than stereotypical voices. These results are difficult to account for in traditional abstractionist views of speech perception, and have a fairly straight-forward explanation in exemplar-based models.

There are however some findings in the literature that seem to pose problems for exemplar-based models. For example, Nygaard et al. (1994) found that familiarity with a talker’s voice resulted in improved word recognition for novel stimuli, not used in training listeners to become familiar with the talker. If, as might be expected from an exemplar-based model, the listener's knowledge of the talkers was based soley upon the exemplars presented during training, then the word recognition gain should have been limited to performance with those particular exemplars.

In summary, research on the talker normalization problem indicates that the listener's perceptual representations of linguistic categories are richly structured, with information about talker identity retained in linguistic representations. One promising modeling strategy that captures the rich internal structure of linguistic categories, while also accounting for processes of generalization, is to model linguistic categories as collections of experienced instances rather than seeing speech perception as a process of mapping variable inputs onto invariant abstract representations.

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Figure 1

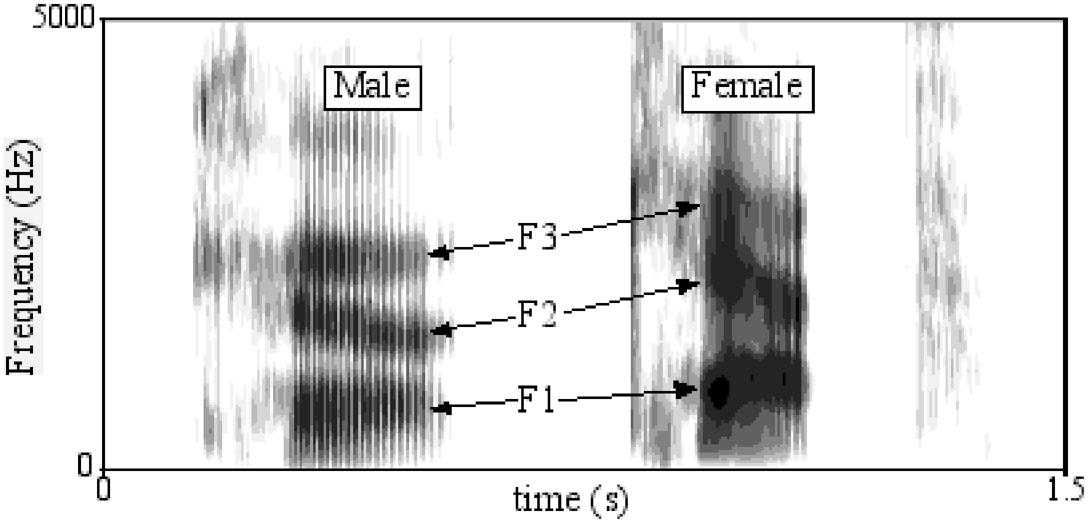

Figure 2

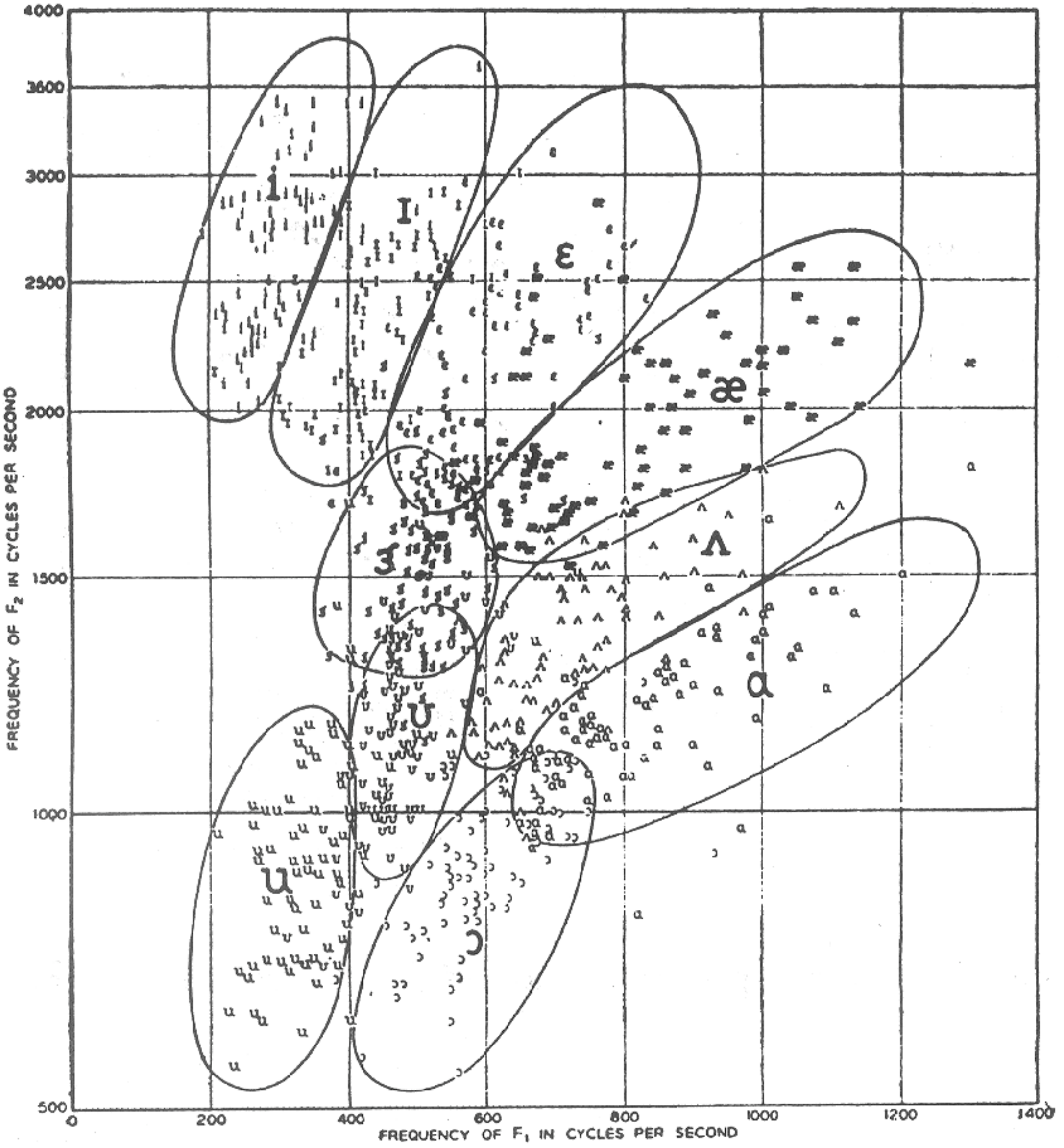
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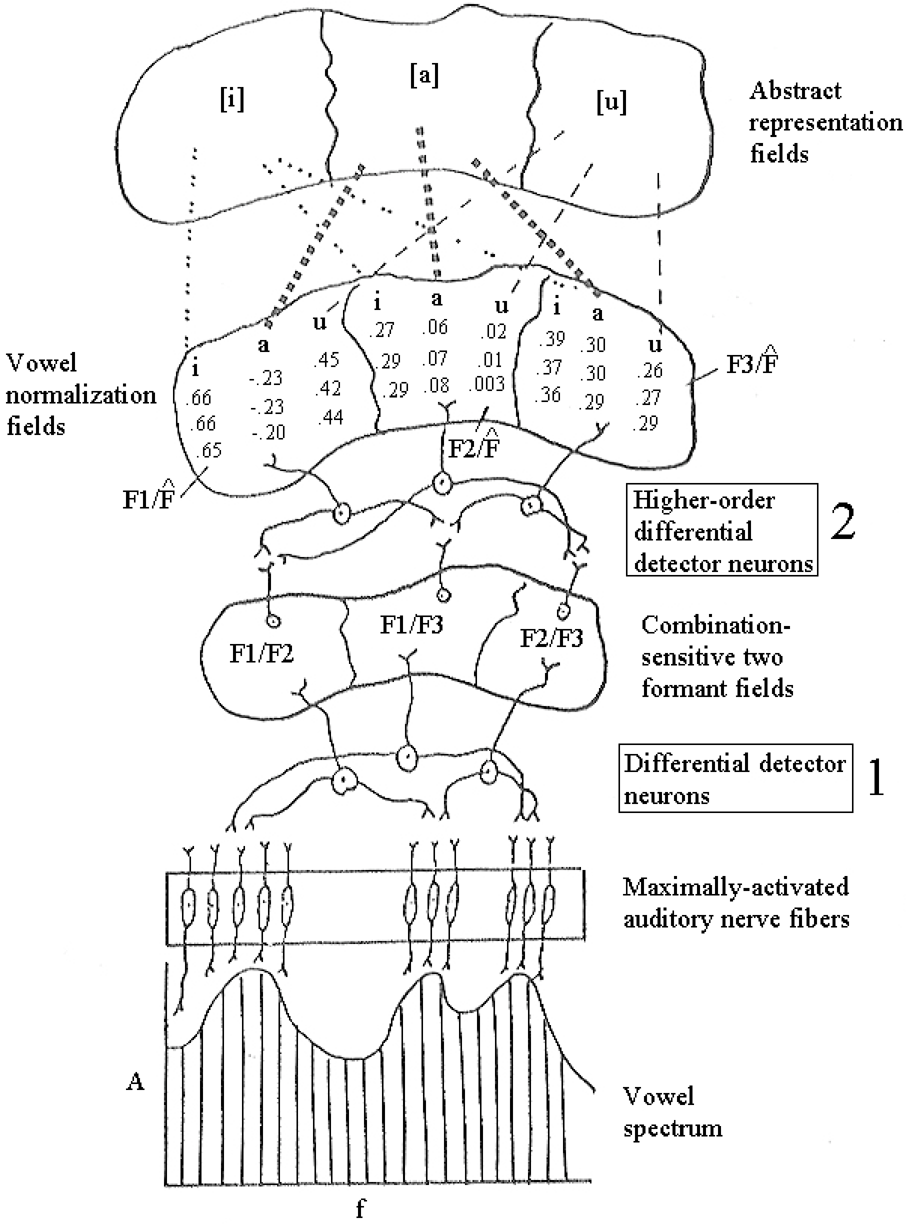
Figure 3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F3/$\hat{F}$
Higher-order differential detector neurons
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F1/F2
F1/F3
F2/F3
Combination-sensitive two formant fields
Differential detector neurons
1
Maximally-activated auditory nerve fibers
A
f
Vowel spectrum

Figure 4 (a)

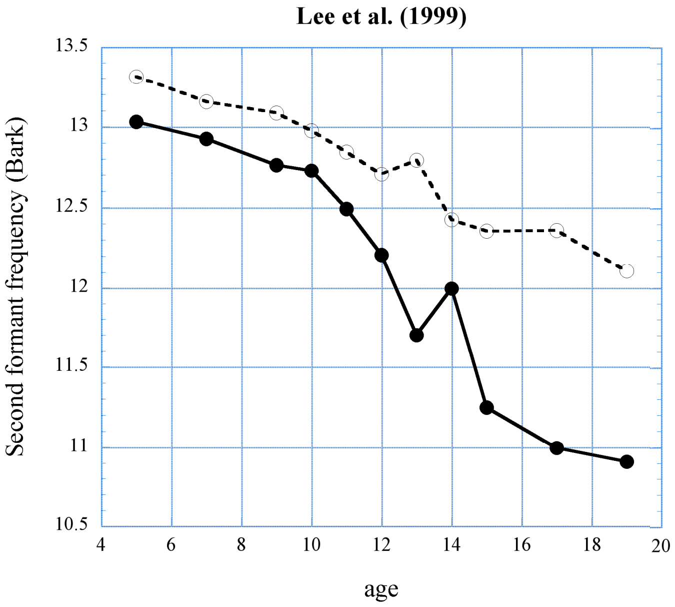


Figure 4 (b)

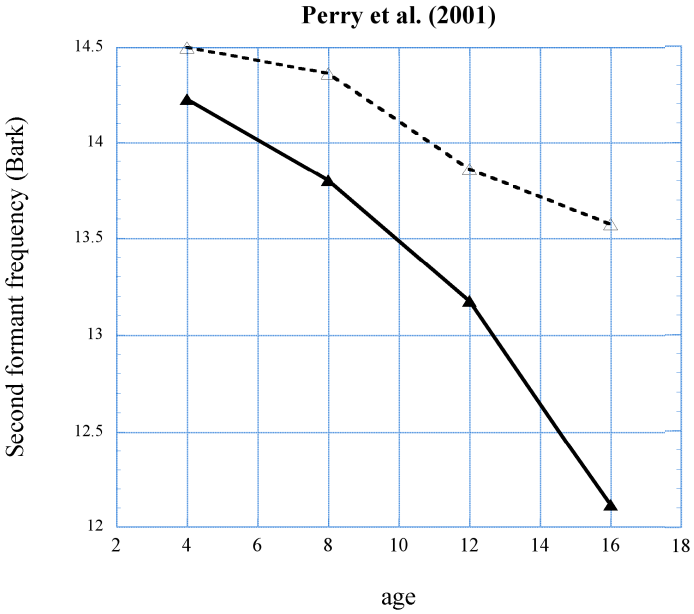
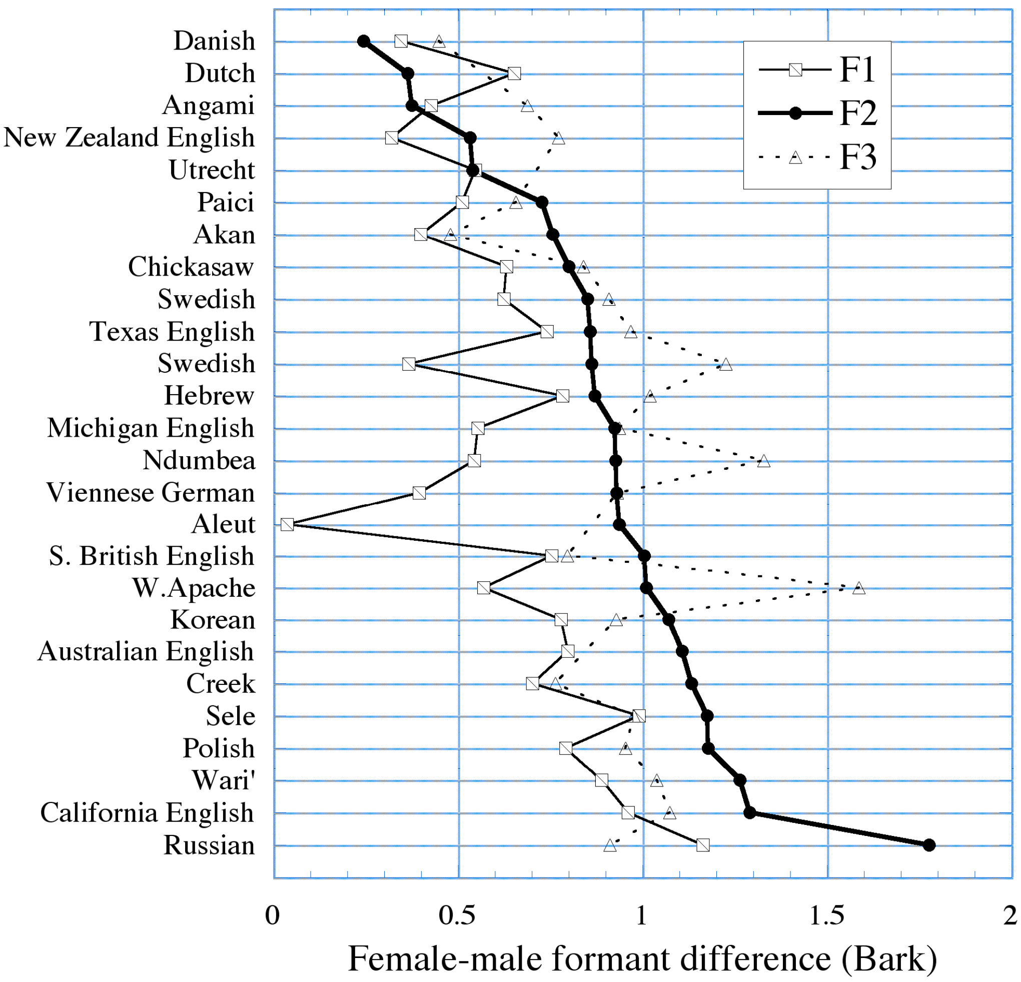


Figure 5


Danish
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Akan
Chickasaw
Swedish
Texas English
Swedish
Hebrew
Michigan English
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Viennese German
Aleut
S. British English
W.Apache
Korean
Australian English
Creek
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Polish
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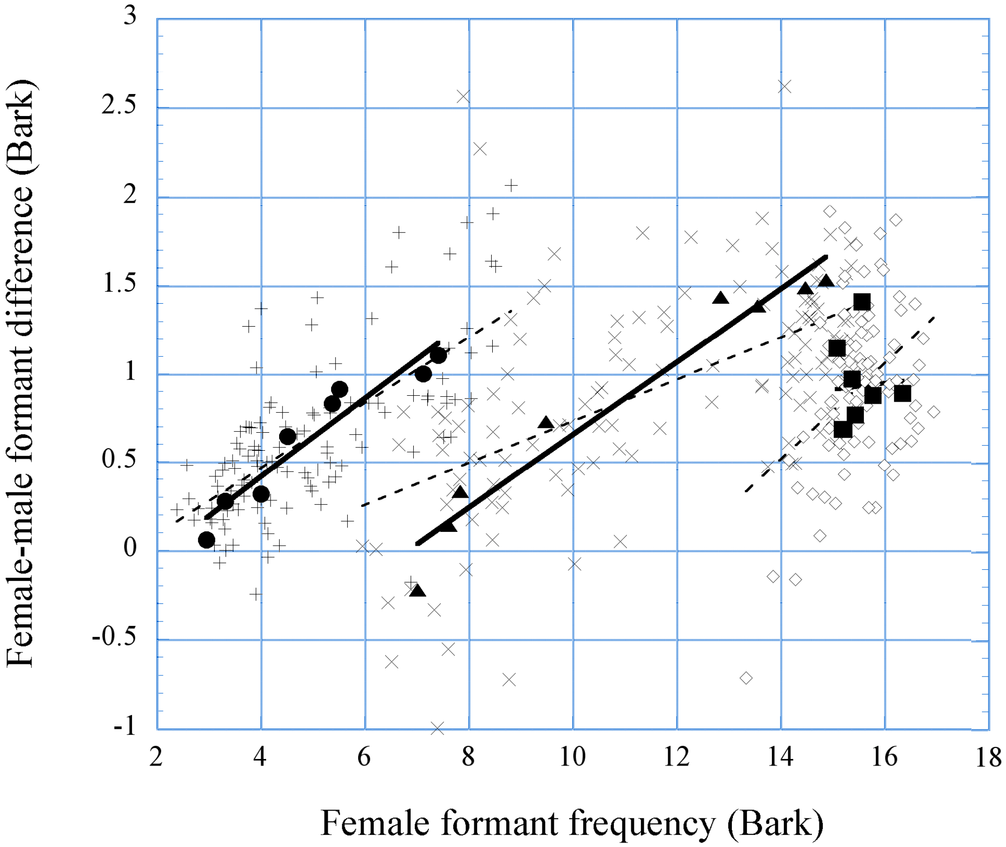
Female-male formant difference (Bark)

Figure 6



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18
Female-male formant difference (Bark)
Female formant frequency (Bark)