SPECTRAL PROPERTIES OF GERMAN AND DANISH SIBILANTS

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Abstract: The Danish sibilants s and ʃ are normally placed auditorily between German s and ʃ in regard to clearness versus darkness. This distribution also seems to be meaningful as regards their acoustic properties. A partial overlapping is often observed between spectra of Danish s and ʃ, whereas the German spectra are always clearly discernible. The spectral shape of the Danish sibilants, especially that of s, seems to be very sensitive to the parameter rounding/non-rounding of a preceding vowel, and occasionally these spectral differences are greater than those between sibilants belonging to different phonemic categories. Danish and German sibilants can be distinguished by their spectral composition. The Danish sibilant spectra normally show two energy maxima, one in the lower and one in the upper part of the frequency range. German spectra normally show but one energy maximum located in the middle of the frequency range for s and in the lower fifth of the frequency range for ʃ.

1. Introduction

Compared to the large number of contributions to the auditory and acoustic description of vowels and stop consonants, very little has been published on fricative consonants. The previous descriptions of the fricative sibilants [s] and [ʃ] have been concentrated either on acoustic cues for auditory recognition of the sibilants or on acoustic descriptions of their spectral compositions, and on a specification of the most simple general parameters needed for a satisfactory generation of synthetic sibilant stimuli.

As for the investigation of perceptual cues of American-English and Swedish fricatives, K.S. Harris (1958) and J. Martony (1962) found that the perception of sibilants depends on the shape of the noise spectrum, not on the variation in vowel transitions, in contradistinction to the perception of other fricative consonants (for instance [f, θ]), which depends mainly on the adjacent vowel transitions. Martony further observed that a typical [f]-spectrum with a 20 dB amplification of its overall intensity was perceived as [s].

In descriptions of the spectral characteristics of sibilants the greatest importance has been attached to the lower part of the spectrum. Jassem (1962 and 1968) and Katarzyna (1968) define four fricative formants, three of which appear in sibilants within the following frequency ranges: F_2 about 1-2 kHz, F_3 about 2-3 kHz, F_4 about 3-5 kHz. The intensity relations and the density of location of these formants are decisive for the distinction between [s] and [ʃ]. Dense formant locations are seen in [ʃ], whereas dispersed formant locations are characteristic of [s]. Jassem gives the formulae: $F_4 - F_2 \geq 1.8$ kHz = [s], $F_4 - F_2 < 1.8$ kHz = [ʃ].

Peter Strevens (1960) identifies 1 kHz as the line of demarcation between formant location density for [s] and [ʃ]. As for intensity levels, Jassem finds that F4 normally has the highest level, F2 the lowest, and F3 is the varying formant in regard to intensity level; in most cases [s] had an F3 with almost the same level as F2, while F3 of [ʃ] had a level close to that of F4. A lower frequency limit is described as the lowest point on the frequency scale at which the energy reaches a level of 20 dB below the maximum level of the spectrum; this gives [ʃ] a low (not more than 2 kHz), alveolar [s] a medium (2 - 3 kHz), and dental [s] a high (more than 3 kHz) lower frequency limit. No unambiguous tendencies were found for the upper frequency limit. The energy of [ʃ] often decreases abruptly at about 7 kHz, but the spectra of some subjects exhibited intensity peaks up to 12 kHz. [s] always had continuous energy up to 12 kHz.

In several reports on synthetic sibilant production the authors start with 4 - 5 poles and 3 - 4 zeroes but find that auditorily acceptable sibilants can be obtained with only 2 poles and 1 zero. Martony, Cederlund, Liljencrants, and Lindblom (1961) mention for [s] a zero at about 3.4 kHz and poles at about 4.2 kHz and 5.3 kHz, for [ʃ] a zero at 1.4 kHz and poles at about 2.1 kHz and 3.1 kHz. Heinz and Stevens (1961) differ by using a second pole in [s] with the center frequency 8 - 8.4 kHz and by giving the zero in [ʃ] a center frequency of 3.4 - 4.4 kHz. Martony also synthesized acceptable [s]-stimuli with one pole at about 3.5 kHz and 2 zeroes at 3 kHz and 5.9 kHz.

It is evident that the details of these results depend on the languages involved, and the more general characteristics must be found in the relative differences between [s] and [ʃ].

2. Recording of the material for the present study

2.1 Choice of material

The present paper is concerned with an acoustic analysis of the spectral properties of German and Danish sibilant fricatives. On the basis of measurements of sections from sonagrams an attempt was made to reveal some differential spectral properties, partly among German and Danish sibilants and partly among sibilants within each of the two languages. The latter type of comparison not only applied to the phonemes /s/ and /ʃ/ but also comprised differences among variants of each of these phonemes in different environments. Needless to say, a considerable individual variation was supposed to occur.

The main part of the material consisted of one list of Danish and one of German words. The words had the structure

(C)(C)V(:)[ʃ,s](ə)(n)

and preconsonantal vowels comprised all the important categories, rounded-unrounded, front-back, and open-close.

It was attempted to find similar words of German and Danish in order to equalize the experimental conditions. The Danish list was spoken by 3 male persons speaking Standard Copenhagen Danish and the German list by 4 male persons, who spoke Standard German (Hochsprache) or an approximation to Standard German.

2.2 Recording procedure

The recordings of the Danish words were made in the studio of the Institute of Phonetics in Copenhagen. The instrumental equipment used was a Brüel & Kjær Condenser Microphone, type 4145, connected with a Brüel & Kjær Microphone Amplifier, type 2603, and the recordings were played on a Lyrec TR 47-2 professional recorder.

The German words were recorded in Cologne at the Institut für Phonetik. The recordings were made in a studio with a Studio Magnetofon M10 taperecorder (Studio-Mischpulteinrichtung) from Telefunken.

Subsequently, sonagrams were made of the words from the list. Equipment used was a Revox A 77 semiprofessional recorder and a Kay-Electric Sonagraph 7027. Two sets of wide band spectrograms were produced: One set with a frequency range of 160 - 16000 Hz (filter width 600 Hz), from which the sections were taken (one section approximately at the middle of each sibilant), and another set with a frequency range of 40 - 4000 Hz. Some uncertainty might be expected in the measurements of frequencies higher than 7 kHz.

3. Preliminary descriptions as a basis for the measuring procedure

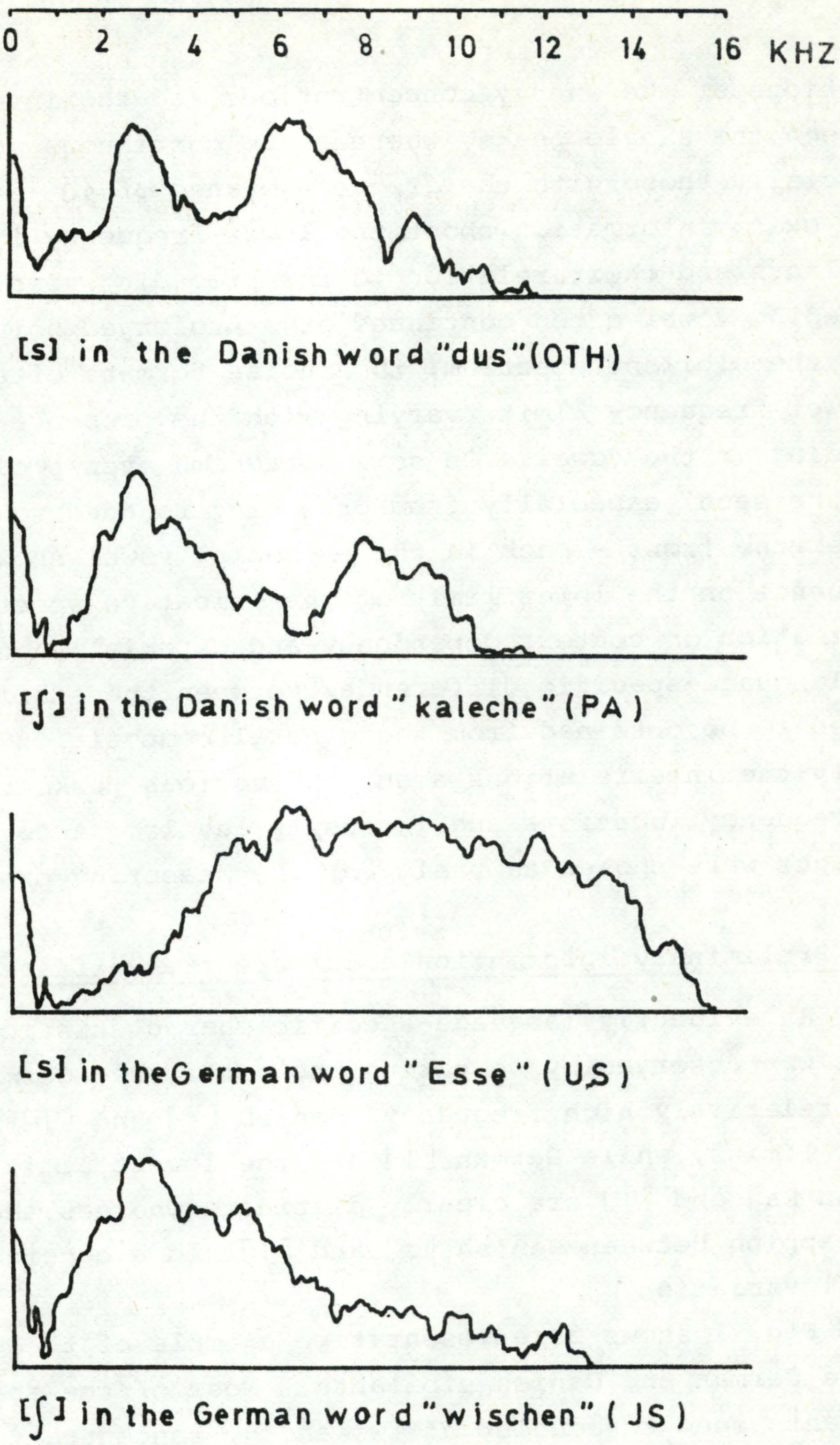
3.1 Spectral composition as basis of description

A comparison between the continuous sonagrams and the sections showed that the sections gave a more detailed impression of the locations of the energy concentrations and the intensity relations between the single peaks, whereas the continuous sonagrams, and especially those with the frequency range of 40 - 4000 Hz, gave a more exact information about the lower frequency limits of the sibilants and their relation to the preceding vowel. F3 of the preceding vowel often continued as a prolonged noise formant into the sibilant spectrum; this noise formant often represented a lower frequency limit, varying with the presence or absence of rounding in the vowel. On some sonagrams even prolongations of F2 were seen, especially from preceding rounded vowels, but the difference front - back in the preceding vowel showed no general influence on the lower limit of the fricative spectrum. The best information on context dependency and especially on the phonemic and language-specific differences between the sibilants still seemed to be obtained from the general composition of the spectra, namely the interrelations among the various peaks both with regard to frequency locations and intensity levels. Accordingly, the sections were chosen as basis for the measuring procedure.

3.2 Preliminary information about spectral differences

An evidently language-specific characteristic of the sibilants was observed by comparing the sections. German [s] starts at a relatively high frequency, Danish [s] and [ʃ] have medium lower limits, while German [ʃ] has the lowest limit. Accordingly, German [s] and [ʃ] are clearly distinct, whereas there is more overlapping between Danish [s] and [ʃ] and a considerable individual variation.

Fig. 1 shows a representative example of the spectral shapes of the German and Danish sibilants. Most of the spectra of Danish sibilants seem to consist of two energy concentrations with a zero in between; each of these humps of energy, henceforth called maxima, consists of various peaks, more or less fused. The sibilants of the subject NRP generally only approached this pattern. The higher maximum was often absorbed in the long decreasing slope



[s] in the Danish word "dus" (OTH)

[ʃ] in the Danish word "kaleche" (PA)

[s] in the German word "Esse" (US)

[ʃ] in the German word "wischen" (JS)

Figure 1

of the lower maximum. The German sibilant spectra rather show a concentration of energy around one large maximum in the central region of the spectrum for [s], and somewhat lower for [ʃ]. In the lower frequency range of both Danish and German sibilant spectra there are peaks which might be compared with the F2 - F3 - F4 of Jassem et al.

3.3 Grouping of the spectra

The previously mentioned context dependency with regard to the presence of rounded - unrounded vowel before the sibilant, turned out to be important. It became clear that a distinction between sibilants in these two environments facilitated the general description. This further made it possible to reduce some of the overlapping between the Danish sibilant spectra to "partial" overlapping caused by the presence or absence of rounding in the preceding vowel; e.g., the spectrum of an [s] following a rounded vowel may be more similar to the spectrum of [ʃ] following an unrounded vowel than to the spectrum of [s] following an unrounded vowel.

The following groupings were undertaken: (a) Danish [s] preceded by an unrounded vowel (abbreviated Da. [s] unround.), (b) Danish [s] preceded by a rounded vowel (Da. [s] round.)[1], (c) Da. [ʃ] unround., and (d) Da. [ʃ] round. The German sibilants were classified in the same way although the distinctions were less clear. Especially the two classes of [ʃ] were found to be very similar, as German [ʃ] is often inherently rounded. As to German sibilants in general, they seem to have a more distinct articulation than the Danish ones, and they are therefore less susceptible to coarticulation. Moreover, all the German vowels were lax, and lax vowels have less pronounced rounding. Anyway, the eight classes were maintained as a basis for the measuring procedure.

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1) The vowel [ɔ], e.g. in the word 'losse', was treated as a rounded vowel, although on some sections it was followed by a sibilant spectrum belonging to class (a).

The difference among the groups was mainly found in the frequency locations of the lower maximum and for some Danish subjects also in the intensity relations between the two maxima. The problem will be discussed in detail in section 4.

4. Measuring procedure

4.1 Peak frequencies as primary parameters

On the basis of the previous observations the following parameters were chosen as relevant for the measurements: Center frequency of the single peaks; center frequencies of the maxima, if any; frequency range of the dominating maximum or prominent part of the spectrum; center frequencies of the zeros; upper and lower frequency limits.

There were normally 10 - 11 measurable peaks in the Danish sibilant spectra, whereas the German sibilants contained 13 - 15 measurable peaks. These peaks were chosen as primary parameters. A close comparison of the center frequencies of the primary peaks within each of the languages revealed certain frequency ranges, within each of which the occurrence of a primary peak was particularly frequent, that is: within the given ranges, there was a peak in all cases, but the relative intensities of the peaks varied for different sound classes depending on place of articulation and on rounding. For example, one peak might have a high intensity and constitute the center of the lower maximum in a [ʃ], whereas a peak of the same frequency in an [s] might appear just as a minor bulge on the rising slope of the lower maximum. Naturally there were cases of fusing or completely lacking peaks in the distribution.

4.1.1 "Basic peaks"

For each of the previous mentioned classes of spectral types (Da. [s] round., Ger. [ʃ] unround., etc.) a set of mean primary peaks were calculated by means of the mean values of the single peak measurements, first for each subject and then for the subjects combined. A comparison of the different sound types revealed that many of the peaks were practically identical and others were so close that they could be united into one, somewhat broader, peak. In this way, a final number of "basic peaks" was set up for each language, for German 14 and for Danish 15, see fig. 2. The number of "basic peaks" for Danish is larger than the number of measurable peaks (10 - 11) in the individual spectra, because the variation both among the subjects and between rounded and unrounded forms of the sibilants was relatively large in Danish.

Within the frequency ranges of the "basic peaks" one should be able to fit in the peak center frequencies of any individual kind of [s, ʃ] from the two languages. Naturally, this description does not involve the claim that there should be a fixed number and fixed location of the resonance frequencies for all sibilant articulations, and an investigation of a larger material might lead to an increased or reduced number of "basic peaks" or partly different frequency ranges for the peaks, but for the purpose of this investigation the present model turned out to be quite useful, if not as a general theory of "basic peaks", then at least as a division of the spectrum which is expedient for comparisons of intensity relations in selected ranges. A division on the basis of frequency alone, e.g. in third octaves or the like, might cut through important peaks. The "basic peak"-model was therefore used as framework for the further description.

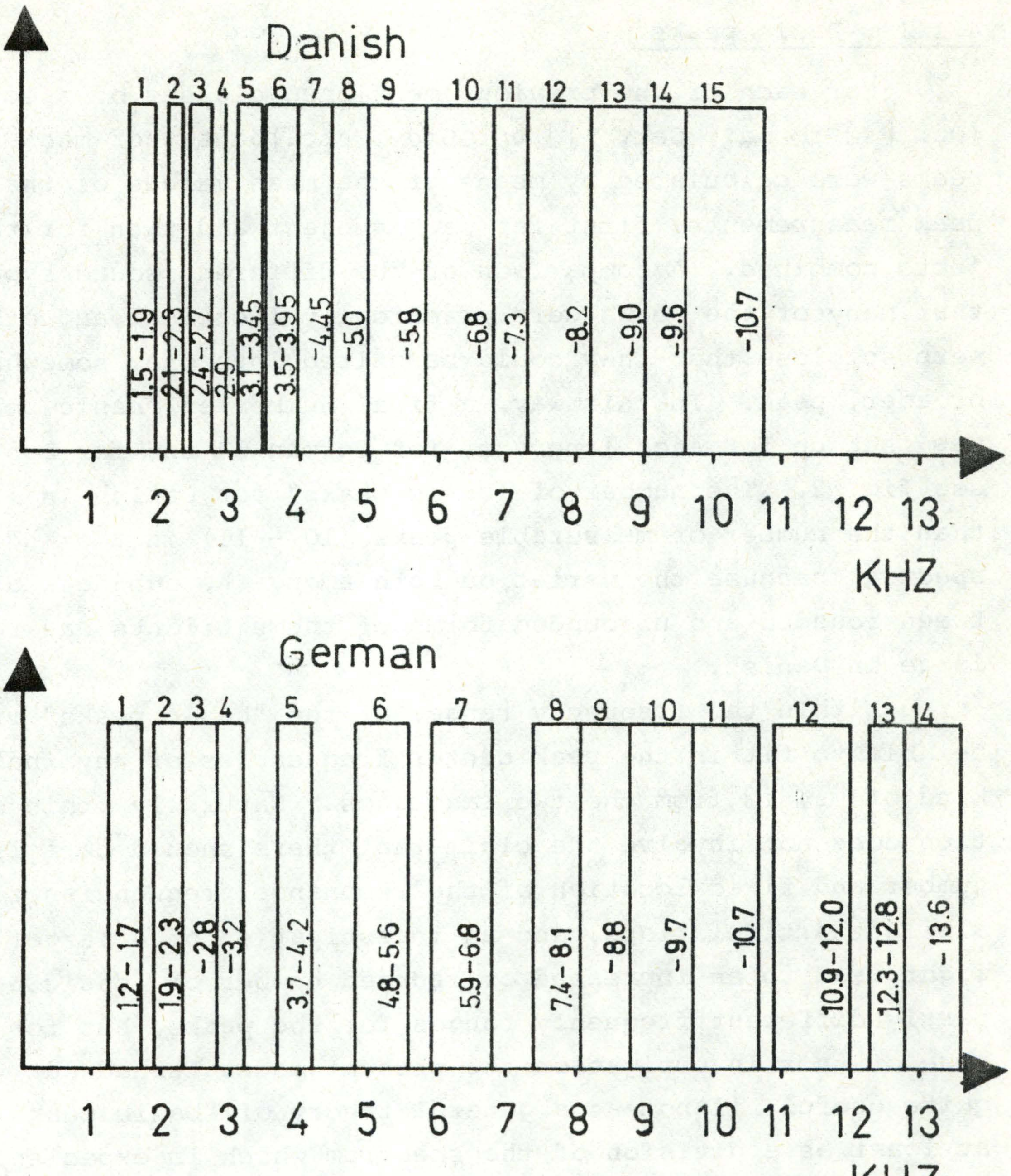


Figure 2
"Basic peaks".

4.2 Ranking of intensity relations

A ranking of the intensity values based on the relation between the peaks of the various classes was preferred to physical scales, partly because a valid calibration of the sections was not available, and partly because of the relatively large differences in over-all intensity among the recordings of the various subjects.

The rank relations among the basic peaks were set up for each individual example, each "basic peak" frequency of the section being given an intensity rank between 1 and 14 or 15, depending on the language. As previously mentioned, only 10 - 11 peaks were measurable in each of the sections of Danish sibilants, therefore one could not expect to find a peak in everyone of the 15 "basic peak" frequency ranges, and in the instances where a basic frequency range contained a slope, the mean level of intensity of this sloping portion was ranked in relation to the other "basic peak" areas of the section.

4.3 Stylized average spectra of sibilants

Now it became possible to calculate the mean intensity relations for a whole group of spectra. The median was chosen as a statistic measure for calculating the mean rank of the "basic peaks" of any desired number of sections. Accordingly, each of the classes (Da. - Ger. [s]-[ʃ] round. - unround.) could be acoustically described by the average rank of the intensity in the "basic peaks". Figs. 3 - 11 show stylized average spectra constructed on the basis of the average intensity ranks of the "basic peaks". The average for each "basic peak" range had to be reproduced as a horizontal line; this was necessary because the (exact) frequency location of the peak within a "basic peak" range might vary for each individual sound. The empty spaces between some of the "basic peaks", especially those of the German sibilants, are supposed to be minor zeros or at least frequency domains with no obvious peaks.

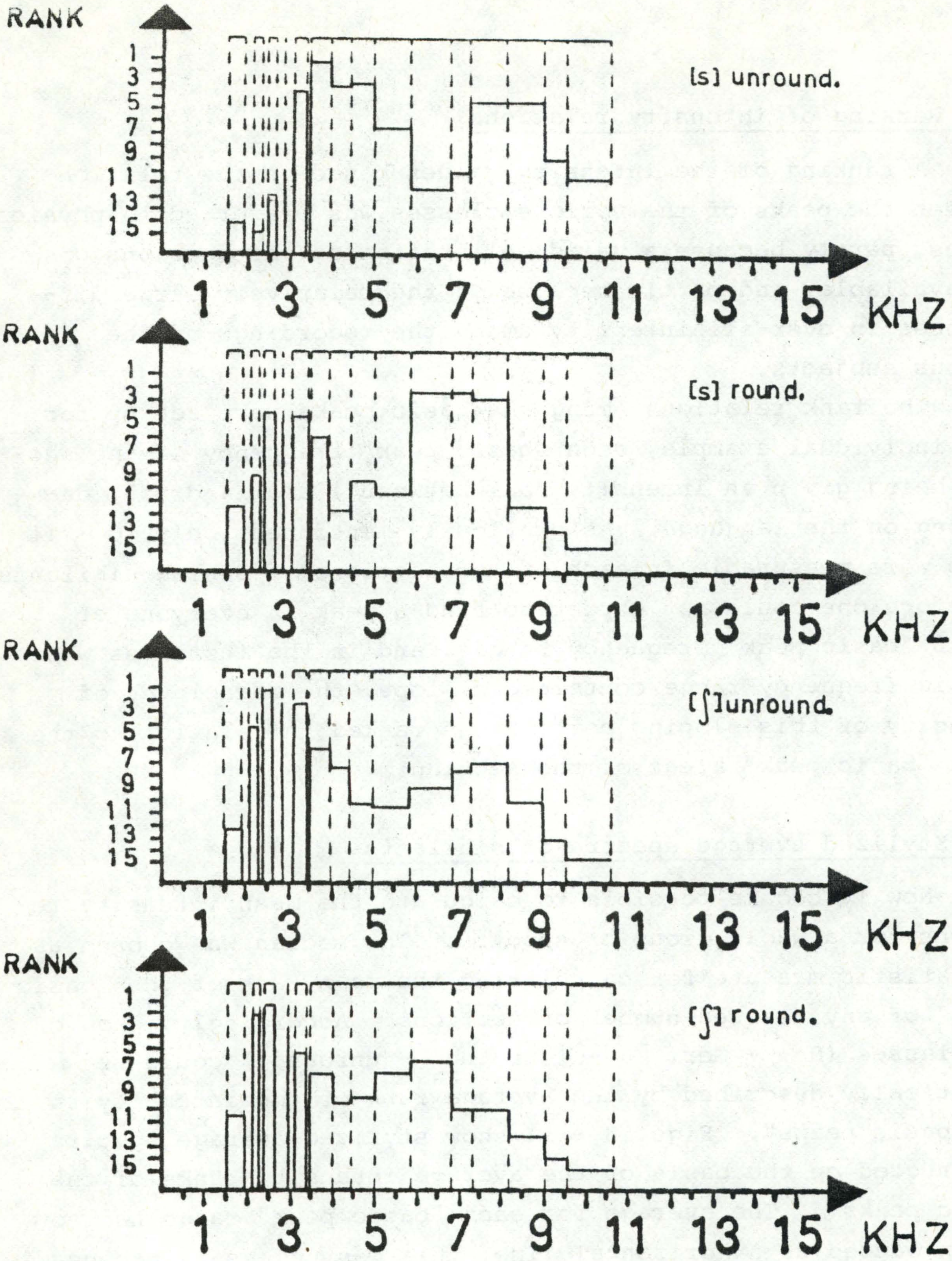


Figure 3

Stylized average spectra (Danish). Subject PA.

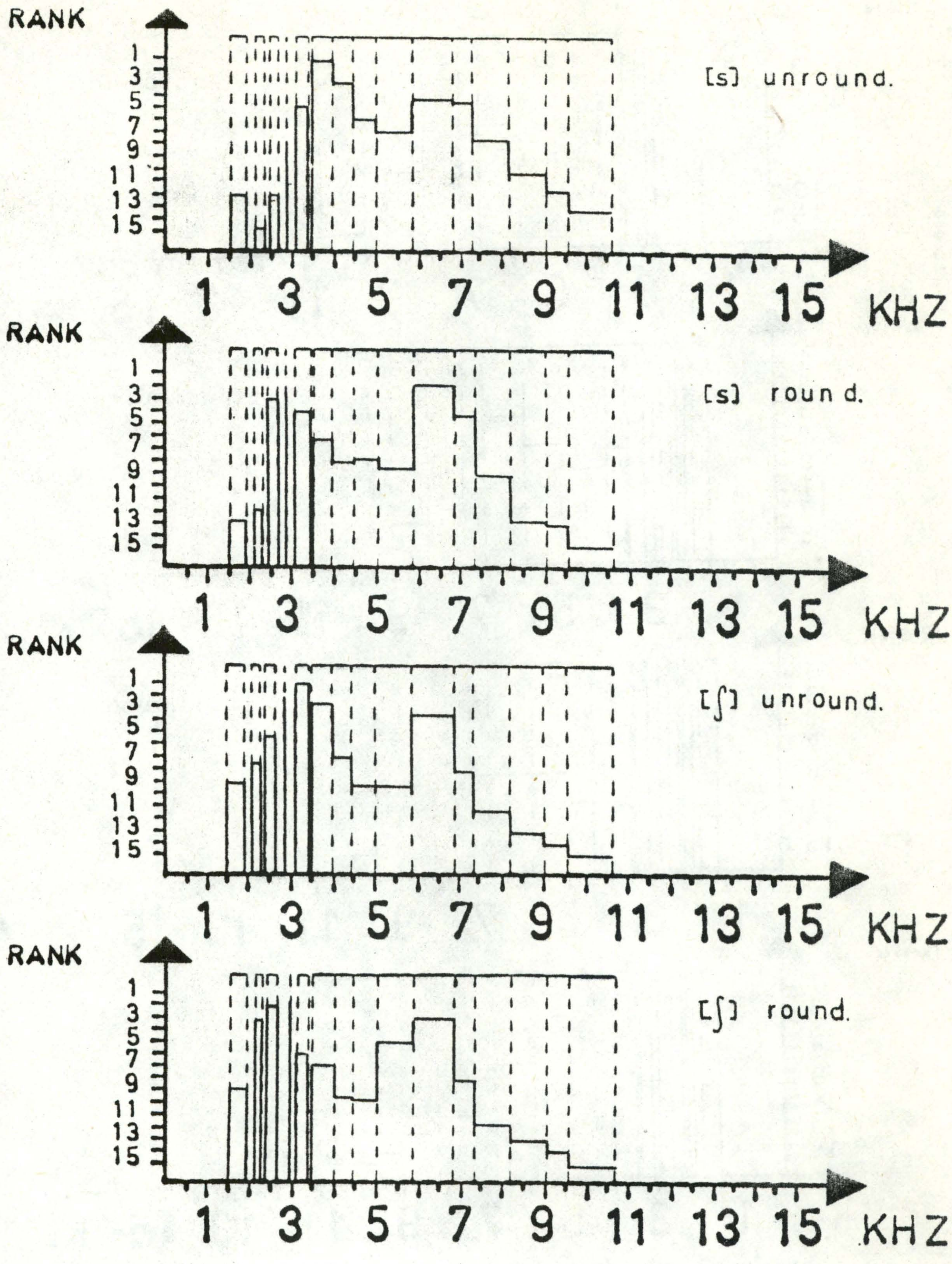
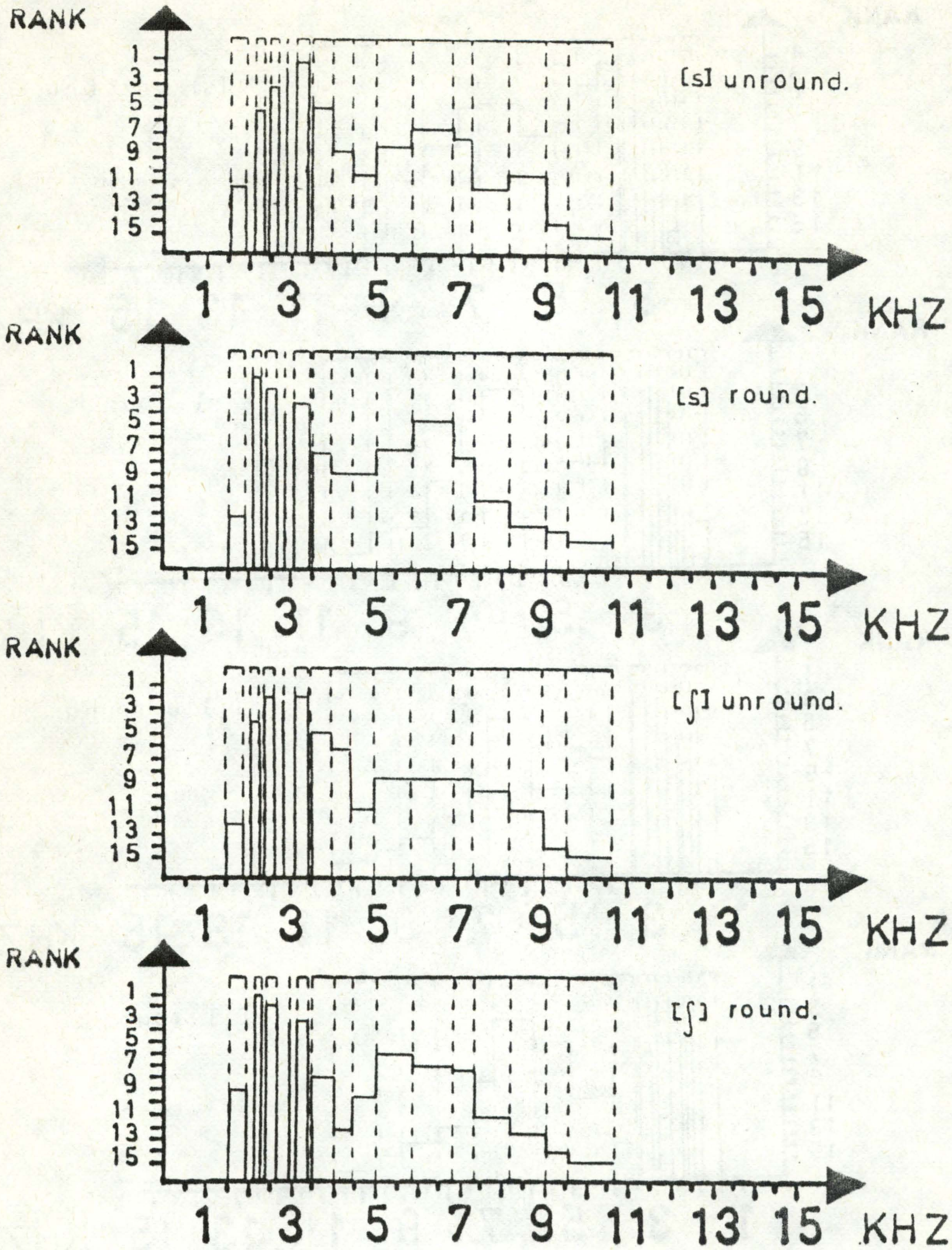


Figure 4

Stylized average spectra
(Danish). Subject: OTH.



<u>Figure 5</u>

Stylized average spectra
(Danish). Subject: NRP.

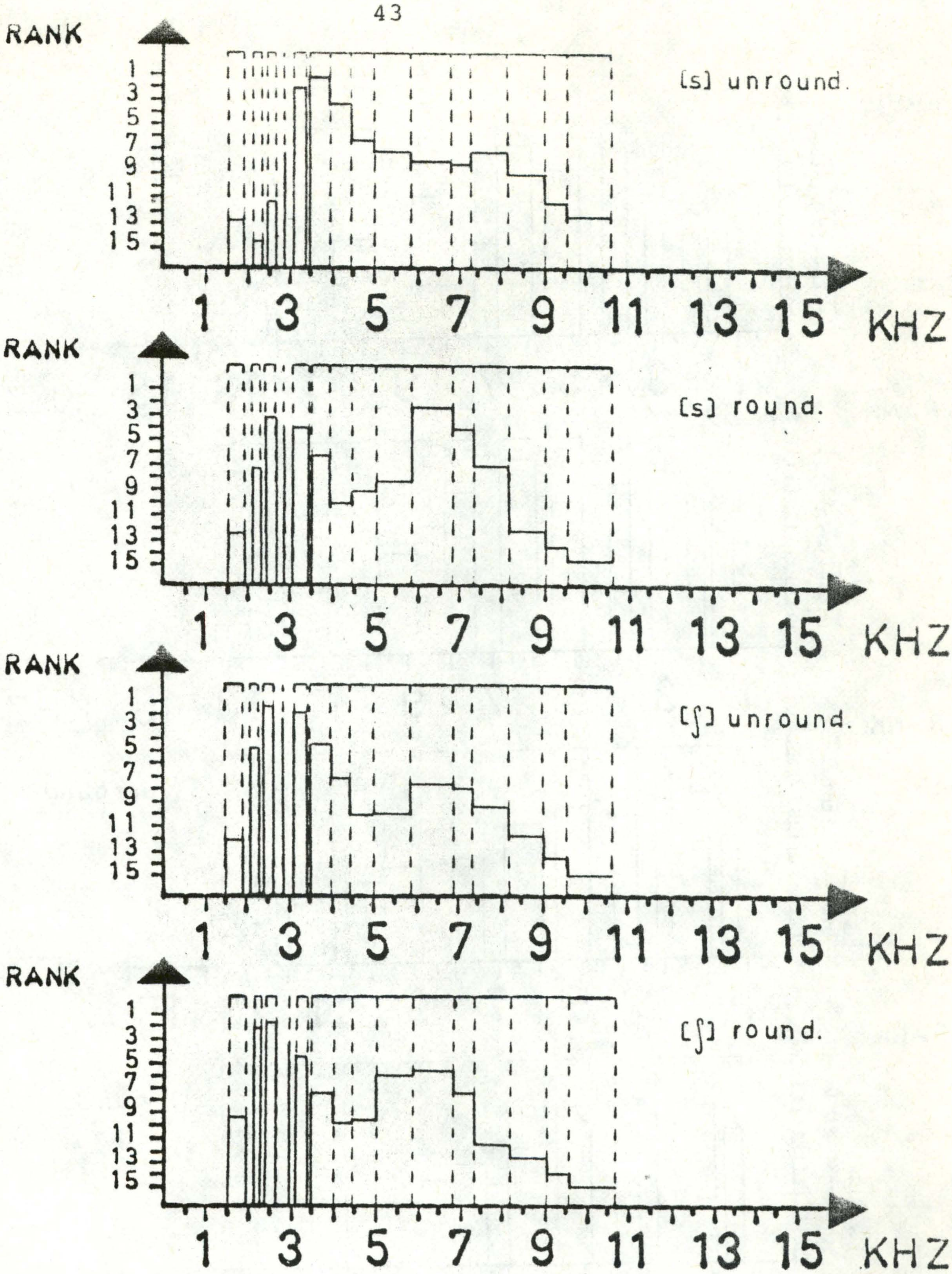


Figure 6

Stylized average spectra (Danish). Average across subjects PA, OTH, and NRP.

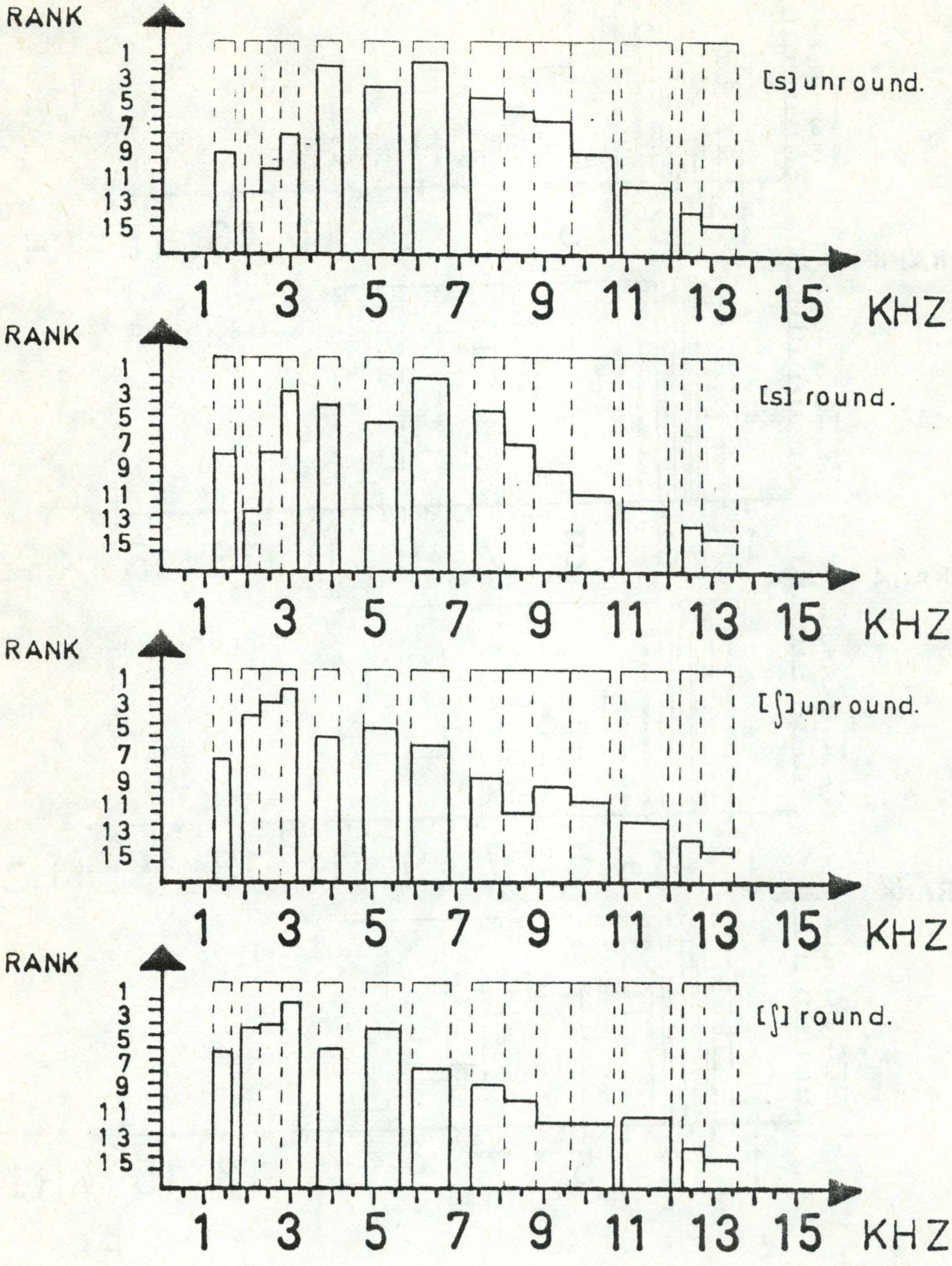


Figure 7

Stylized average spectra (German). Subject: PS.

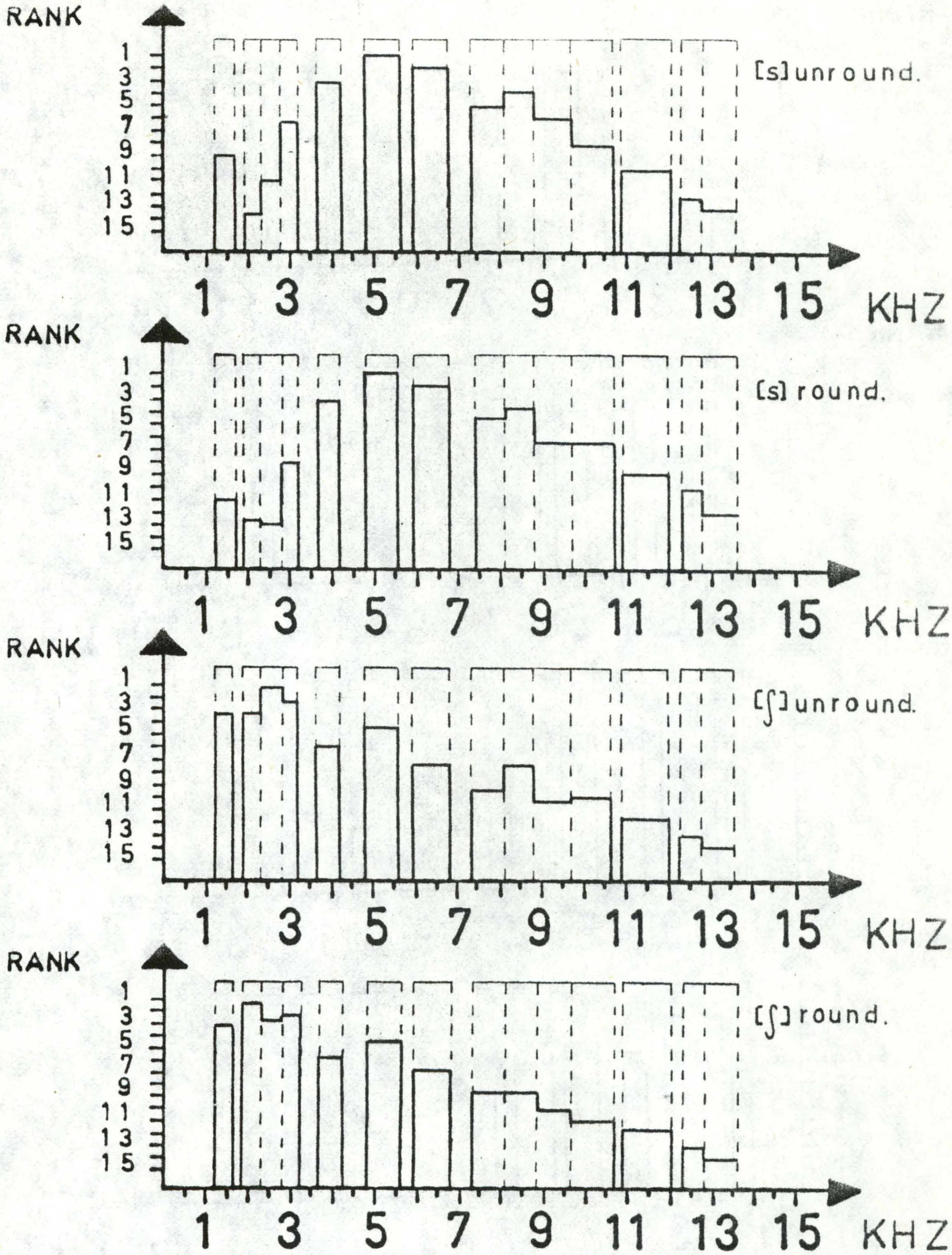


Figure 8

Stylized average spectra
(German). Subject: HH.

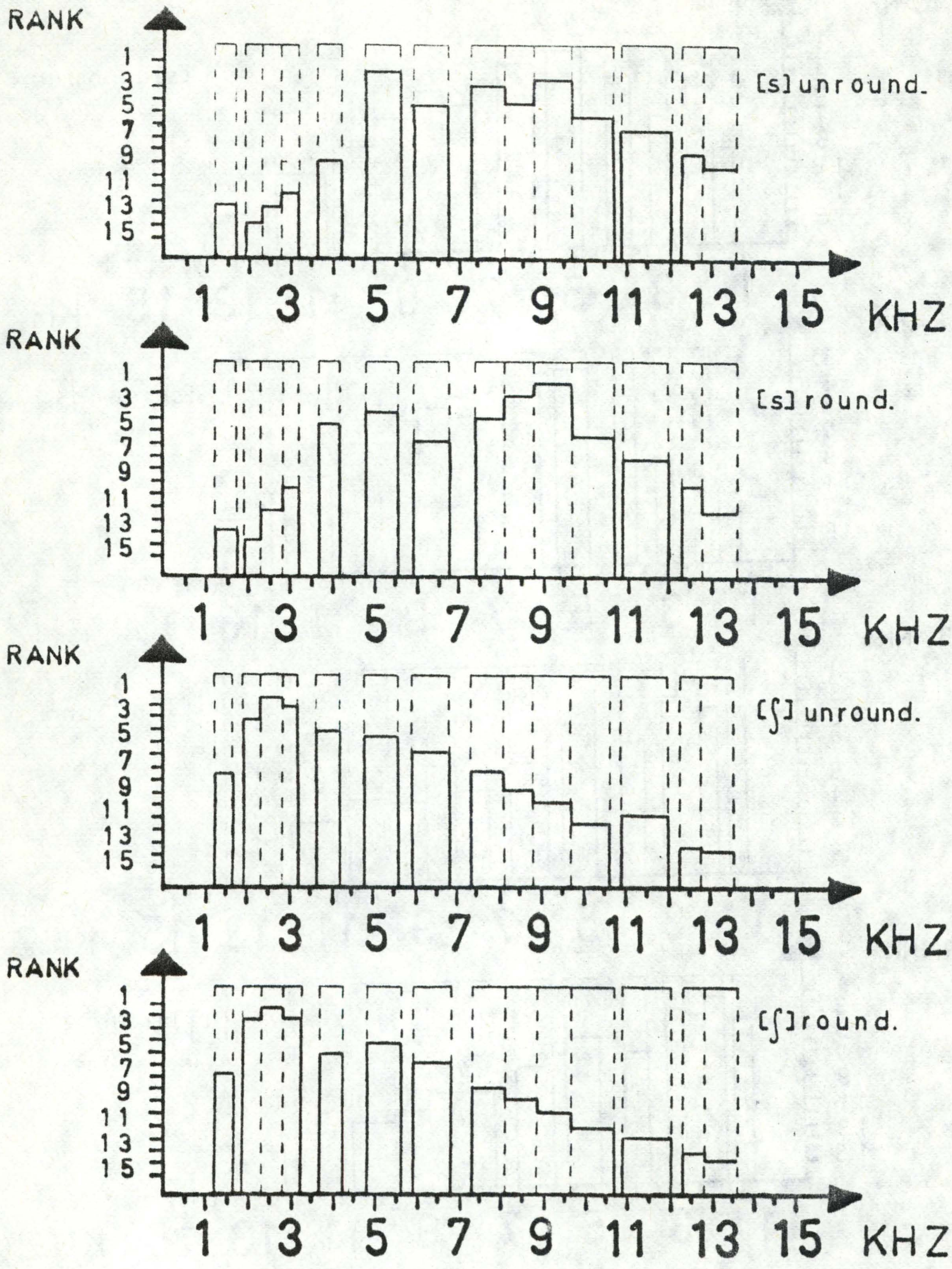


Figure 9

Stylized average spectra
(German). Subject: US.

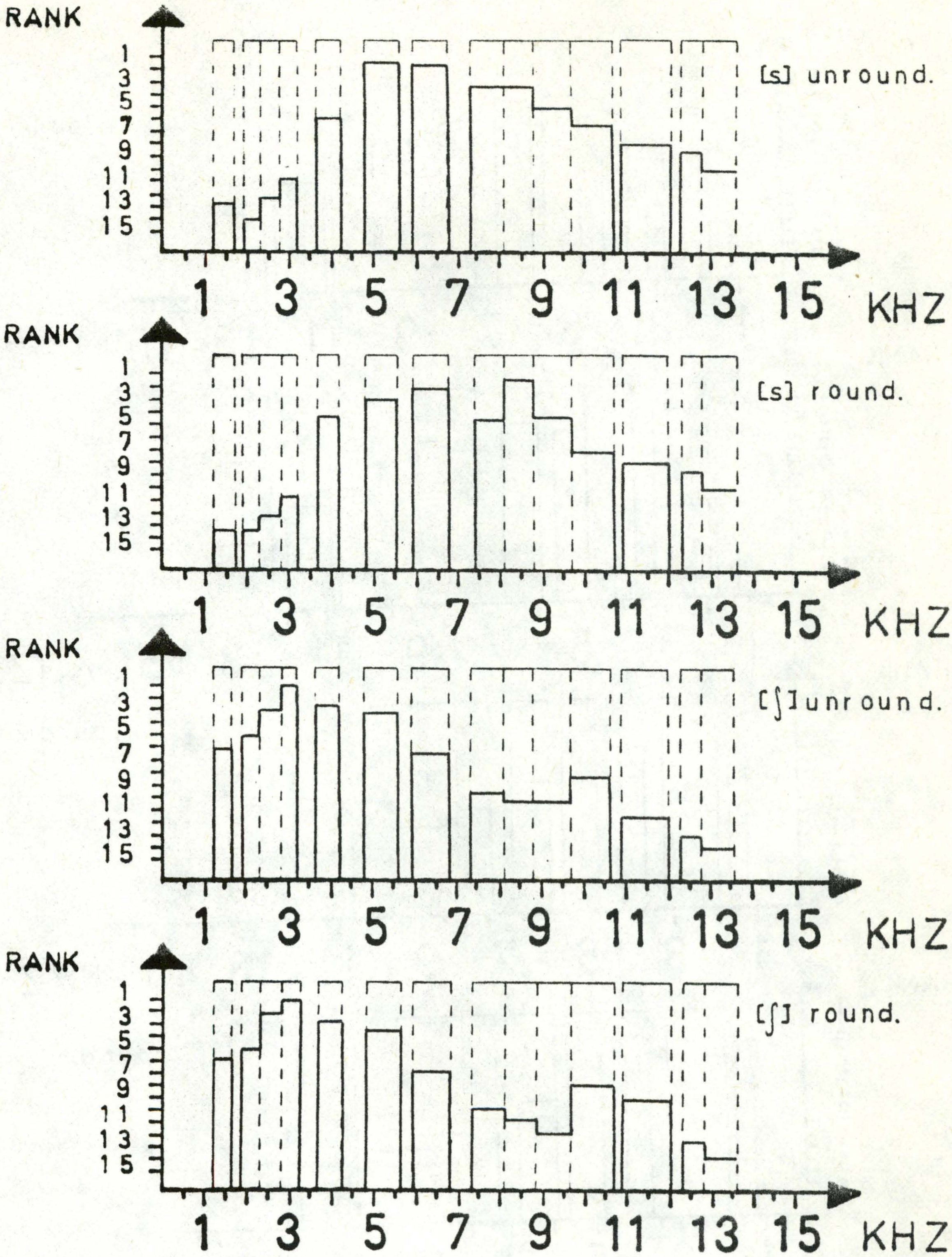
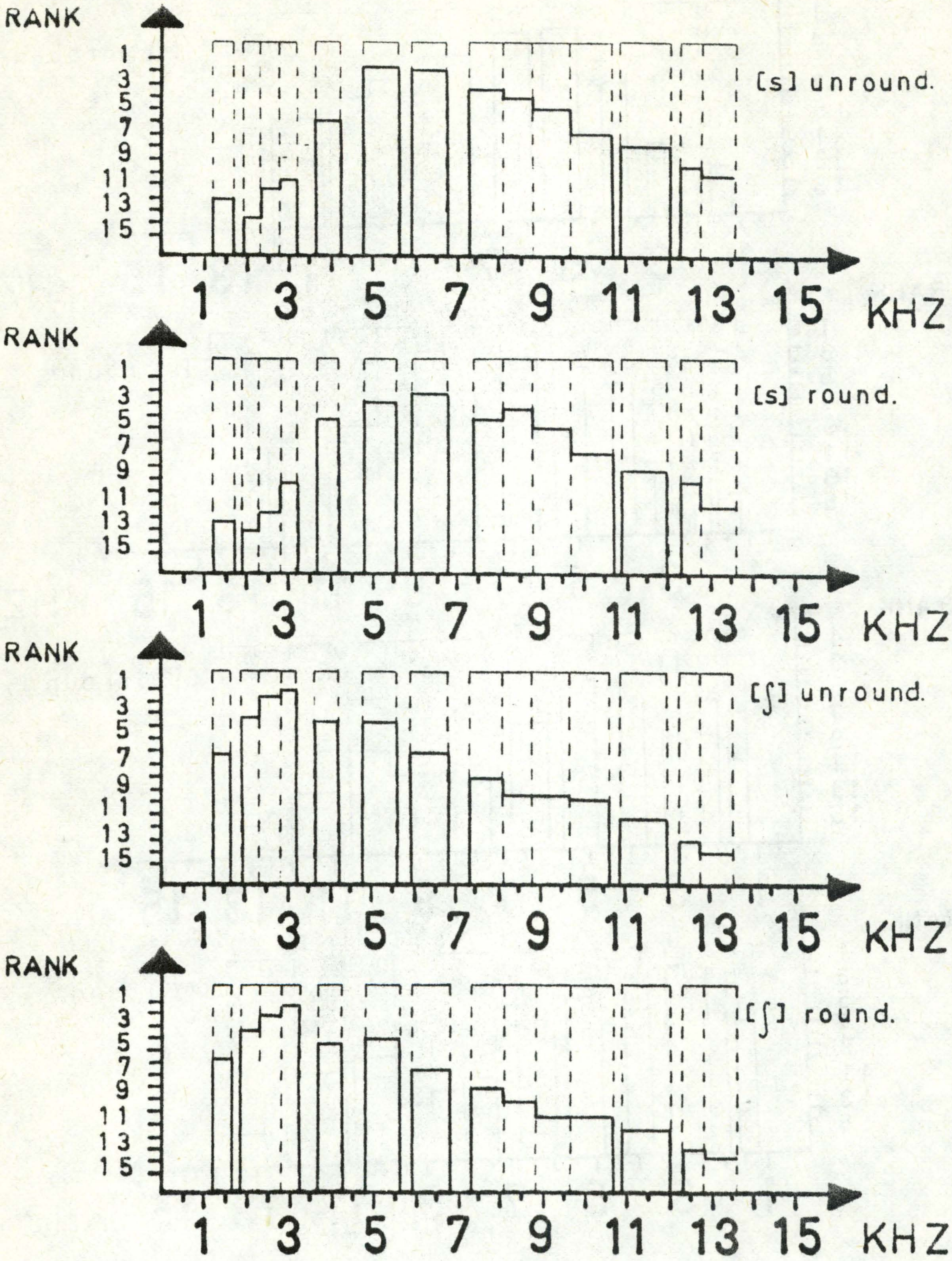


Figure 10

Stylized average spectra
(German). Subject: JS.



<u>Figure 11</u>

Stylized average spectra (German). Average across subjects PS, HH, US, and JS.

5. Results and discussion

On the basis of the stylized average spectra and the preliminary observations supported by the physical measurements the following tentative general characteristics of the classes can be put forward:

5.1 Spectral properties of Danish sibilants

5.1.1 Sibilant preceded by rounded versus unrounded vowel

This difference is manifested most clearly in the [s]-spectra and appears in the following ways:

When the sibilant is preceded by a rounded vowel the intensity of the lower maximum is relatively weak, while the intensity of the higher maximum is relatively strong (see figs. 3 and 4).
In several cases the upper maximum is dominant, whereas the lower maximum is usually dominant before unrounded vowels.

The center frequency of the lower maximum is lower after a rounded vowel (see figs. 3-6).
Average differences are greatest for the [s]-spectra: [s] unround. 3800 Hz - [s] round. 3000 Hz; [ʃ] unround. 3000 Hz - [ʃ] round. 2800 Hz.

The frequency range of the increasing slope of the lower maximum is smaller after rounded vowels.
Here the measurements show the averages:
[s] unround. 2250 - 3300 Hz - [s] round. 2100 - 2400 Hz;
[ʃ] unround. 1650 - 2450 Hz - [ʃ] round. 1600 - 1900 Hz.

Decrease of the energy in the upper part of the spectrum starts earlier after rounded vowels (see figs. 3-5).
This tendency can hardly be observed for the subject OTH
Average for all subjects:
[s] unround. 8450 Hz - [s] round. 7750 Hz; [ʃ] unround. 7250 Hz - [ʃ] round. 6050 Hz.

The valley (zero) between the two maxima has a lower center frequency after rounded vowels (see especially fig. 3).

This is only obviously true for subject PA.

On the whole, a general shift downwards of the spectral energy takes place after a rounded vowel, but at the same time the central point of energy shifts upwards on the frequency scale, that is, the peaks within the two maxima are shifted upwards. The rather dubious measurements of absolute upper and lower frequency limits show the shift downwards:

[s] unround. 1550 - 11950 Hz - [s] round. 1300 - 11600 Hz
[ʃ] unround. 1300 - 11000 Hz - [ʃ] round. 1200 - 10400 Hz

5.1.2 General differences between Danish [s]- and [ʃ]-spectra

Here the interesting problem arose that it seemed almost impossible to find general acoustic differences in [s]- versus [ʃ]-spectra, especially for the two subjects OTH and NRP. One pronounced difference seems to be:

[ʃ] has a decisive decline of upper spectral energy at lower frequencies than [s].

This is obvious in most of the spectra, and the average measurements are:

[s] 8050 Hz - [ʃ] 6850 Hz.

On the whole, the [ʃ]-spectra seem to be shifted somewhat toward lower frequencies, but this information must be taken with reservation, as the differences in environment (viz. preceding unrounded versus rounded vowel) causes quite a dispersion in the total averages of the measurements of each sibilant.

A comparison of [s] and [ʃ] preceded by the same vowel category shows clearer differences, especially after unrounded vowels, but in several cases the differing features seem to be individual. The [s]- and [ʃ]-spectra of subject NRP are so similar that a general distinction between them can hardly be made, even when they are paired according to vowel categories.

There seems, however, to be a slight tendency for the [ʃ]-spectra to have a slightly higher amount of energy concentrated in the lower maximum, a little less in the upper maximum which seems to be shifted a little down the frequency scale (see fig. 5).
Measurements for NRP are:
Frequency range of the dominant part of the spectrum:

[s] unround. 2000 - 4350 Hz - [ʃ] unround. 1600 - 4650 Hz
[s] round. 1850 - 4350 Hz - [ʃ] round. 1550 - 4150 Hz.

Frequency range of the decisive increase of intensity leading up to the lower maximum:

[s] unround. 2000 - 2850 Hz - [ʃ] unround. 1500 - 2450 Hz
[s] round. 1850 - 2100 Hz - [ʃ] round. 1350 - 1950 Hz.

Center frequency of the lower maximum as a whole:

[s] unround. 3350 Hz - [ʃ] unround. 3050 Hz;
[s] round. 2900 Hz - [ʃ] round. 2800 Hz.

For the other two subjects the same differences can be observed, but more pronouncedly. The [ʃ]-spectra contain more energy in the lower part of the spectrum and the increase of intensity leading up to the lower maximum begins at lower frequencies than for [s] (the difference may amount to 1300 Hz), and a general weakening of the upper spectral energy (see figs. 3 and 4). The measurements are as follows:

Frequency range of the decisive increase of intensity leading up to the lower maximum:

[s] unround.	PA: 2400 - 3500 Hz	OTH: 2250 - 3450 Hz
[ʃ] unround.	PA: 1600 - 2300 Hz	OTH: 1700 - 2650 Hz
[s] round.	PA: 2100 - 2500 Hz	OTH: 2200 - 2600 Hz
[ʃ] round.	PA: 1550 - 2100 Hz	OTH: no measurements.

Center frequency of the lower maximum as a whole:

[s] unround.	PA: 4000 Hz	OTH: 3800 Hz
[ʃ] unround.	PA: 2900 Hz	OTH: 3200 Hz
[s] round.	PA: 3100 Hz	OTH: 2950 Hz
[ʃ] round.	PA: 2750 Hz	OTH: no measurements.

It is interesting to notice the previously mentioned partial overlapping between the phonemic categories: Danish [ʃ] preceded by an unrounded vowel may have a higher center frequency of the lower maximum than Danish [s] preceded by a rounded vowel.

Beside the previously mentioned general difference between [s] and [ʃ], namely the decrease of upper spectral energy located at lower frequencies in [ʃ], also the frequency range 1500 - 2500 Hz seems to contain crucial information as to the general differences between [s] and [ʃ] in Danish.

5.2 Spectral properties of German sibilants

5.2.1 Sibilant preceded by rounded versus unrounded vowel

This problem seems easier to handle for German sibilants. For the spectral shape of [ʃ] it apparently makes no difference whether [ʃ] is preceded by a rounded or an unrounded vowel. As mentioned in a previous section, [ʃ] is frequently articulated with rounded lips, and besides German sibilants have a more distinct articulation than Danish ones and are therefore less affected by coarticulation.

The fact that the German rounded lax vowels are frequently articulated with no pronounced lip rounding also seems to neutralize the influence of coarticulation to a certain degree. One of the subjects (PS) has long tense rounded front vowels in two of the words, and this fact has made his spectra of [s] unround. and [s] round. differ more than those of the other subjects, who articulated a lax [Y] in this position (see fig. 7 vs. figs. 8-10). Accordingly, one might expect that long tense vowels preceding the sibilant would bring out a clearer distinction between [s] unround. and [s] round. Moreover, the small differences that can be observed between [s] unround. and [s] round. in this material exhibit individual variation. A varying amount of extra energy is seen in the frequency ranges of "basic peak" no. 4 or 5 (3000 - 4000 Hz), furthermore, coarticulation from a preceding rounded vowel seems to cause a slight increase of intensity at about 8000 - 9500 Hz, but generally this material showed no consistent distinctive spectral properties. The individual variation is very small; the [ʃ]-spectra, especially, are similar for all the German subjects.

5.2.2 The difference [s] - [ʃ] in German

In contradistinction to Danish the German [s]- and [ʃ]-spectra differ fundamentally without regard to the preceding vowel. All of the [ʃ]-spectra have their main energy in the lower part of the spectrum with a maximum centered at about 3000 Hz, from which one may observe a slight decrease of energy up to "basic peak" no. 7 (about 5800 Hz) and a steeper decrease above that frequency region. All the [s]-spectra have almost no discernible energy in the [ʃ]-maximum, whereas their maximum of energy is concentrated in the central region of the spectrum, in the "basic peaks" nos. 6-7 (4800 - 7600 Hz) (see fig. 11).

5.3 The difference between Danish and German sibilants

Auditorily the Danish sibilants [s] and [ʃ] are normally placed in between German [s] and [ʃ] with regard to the clearness versus darkness of the noise (clear - dark: German [s] Danish [s] Danish [ʃ] German [ʃ]) and, not surprisingly, an overlapping of acoustic distinctions was found only in Danish, not in German, sibilant spectra. The acoustic distinction between on one hand Danish and German [s] and on the other hand Danish and German [ʃ] is rather obvious.

The clearest language-specific acoustic type is represented by the double-peaked Danish sibilant spectra (as for subject NRP, see section 3.2). The tendency to a configuration: lower maximum - zero - upper maximum is most apparent for Danish [s]-spectra. The German [s]-spectra generally show one single maximum near the center of the frequency range. The German [ʃ]-spectra likewise contain a single maximum, but it is shifted downwards and has a more slowly declining upper intensity slope.

Further, the German sibilants show energy at higher frequencies than the Danish ones. The measures of absolute upper frequency limits are:
Da. [s] 11800 Hz - Ger. [s] 14100 Hz; Da. [ʃ] 10800 Hz - Ger. [ʃ] 12900 Hz.

In the lower part of the spectrum the decisive increase of energy of German [s] starts at about 2500 Hz higher than for Danish [s], that is somewhere near the zero between the two maxima of the Danish average spectra. The absolute lower frequency limit differs only slightly for Danish and German [s]-spectra. German [ʃ]-spectra show energy at lower frequency locations than do Danish [ʃ]-spectra. Values for absolute lower frequency limits are:
Ger. [ʃ] 950 Hz - Da. [ʃ] 1300 Hz.
Frequency locations of points above which there is a decisive increase of lower spectral energy:
Ger. [ʃ] 1050 - 1800 Hz - Da. [ʃ] 1600 - 2250 Hz.

5.4 General differences among sibilant spectra

5.4.1 Spectra of sibilants preceded by rounded versus unrounded vowels

Generalizations of common acoustic properties of [s]- and [ʃ]-spectra naturally have to be made with strong reservations. Still, there are some differences between sibilants preceded by rounded versus unrounded vowel which are common to Danish and German and might reflect a general tendency. For both languages a rounded vowel before the sibilant (if the sibilant itself is not characterized by obvious liprounding) causes an amplification of the energy immediately below the dominant energy maximum of the sibilant spectrum. This may be due to the fact that liprounding causes a lowering of the formant frequencies (the poles of the transfer function).

The difference rounded - unrounded vowel before the sibilant seems to affect [s] more than [ʃ]. (As previously mentioned, German [ʃ] does not seem to be affected at all.) An explanation of this may be the fact that the influence of rounding on formant frequencies depends on the place of articulation (constriction of the resonator). F4 is thus more affected by rounding if the primary constriction is situated in the front of the mouth (as in [s]) and less affected if the primary constriction is made somewhat further back (as in [ʃ]). The place of articulation of [ʃ] may vary, but the center of the constriction will always be situated further back than that of [s].

5.4.2 General differences among [s]- and [ʃ]-spectra

Even here the tendencies must be stated with strong reservations. In the present material two features were observed that separate [s] from [ʃ] acoustically: [ʃ] had stronger energy in the lower part of the spectrum relative to [s] and a steeper decline of energy in the upper part. The strong reservation to the generalizations is due to the large individual variation among the Danish subjects; for instance, the spectra of [s] and [ʃ] unround. by the subject NRP showed acoustically greater similarity than did the spectra within the same class produced by the other Danish subjects.

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