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ADAPTATION STUDIES
IN RESIDUE PITCH

by

Joseph W. Hall, III

A Dissertation Submitted to
The Faculty of the Graduate School at
the University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

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Approved by

D. R. Soderquist
Dissertation Adviser

APPROVAL PAGE

This dissertation has been approved by the following committee of the Faculty of the Graduate School at the University of North Carolina at Greensboro.

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HALL, III, JOSEPH W. Adaptation Studies in Residue Pitch. (1976) Directed by: Dr. D. R. Soderquist. Pp. 62.

Residue pitch perception in the human (three subjects with normal hearing) was examined with the psychophysical technique of adaptation. In this method an adaptation residue pitch of a particular value was presented for 30 seconds and its effect on the perceptibility of a test residue pitch of particular value was noted. Several aspects of residue pitch were studied: the channel specificity for residue pitch with regard to complexes made up of both low and high spectral composition; adaptation of a residue pitch arising from components of a particular spectral region by the same pitch arising from components of a different spectral region; the number of pitch cues or components necessary to adapt a residue pitch channel; the importance of temporal fine structure in adapting pitch-specific channels; and the relation between pure tone and residue pitch. All studies were performed with the adaptation and test stimuli presented to the same ear (monaural) and with the adaptation and test stimuli presented to different ears (binaural).

It was found that there seem to be residue pitch chan-

nels that are specifically sensitive to a pitch arising from a particular spectral region presented to a particular ear. However, channels specific for a residue pitch usually seem to be somewhat sensitive to spectral information for that pitch, regardless of ear of presentation or whether the spectral composition is low or high. Pitch channels specialized for low spectral composition are narrower (sensitive to fewer residue pitches) than channels specialized for high spectral composition.

At least two residue pitch cues were found to be necessary for the adaptation of a residue pitch channel, and pitch channels were found to be insensitive to temporal fine structure. Residue and pure tone pitch seemed to be extracted by different mechanisms, having independent channels.

The data were discussed in terms of specialized channels for pitch extraction. The application of the data to current theories of pitch perception was also discussed.

ACKNOWLEDGMENTS

Thanks are extended to Drs. Harter, Shull, Smith, and Whitlock for their helpful and insightful suggestions. Special thanks is given to Dr. David Soderquist for his support and continued help in solving the problems, both technical and intellectual, which arose during this endeavor.

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CHAPTER I

INTRODUCTION

One of the most basic psychological attributes of sound is pitch. Even though all "natural" sound sources produce stimuli with many harmonics or overtones, the pitch perceived is generally that of the fundamental. For instance, when a piano or saxaphone plays middle C, or if this pitch is hummed by the human voice, the fundamental is accompanied by as many as 40 multiples (harmonics) of the fundamental; yet the pitch perceived is that of the fundamental, not that of the harmonics. One of the earliest interpretations of this phenomenon was that the fundamental determined pitch because it was the harmonic of greatest intensity (Helmholtz, 1863/1930). There have been several objections lodged against this contention. One is the fact that in some musical instruments the fundamental is not the most intense harmonic; the pitches played by these instruments are nevertheless judged to correspond to the fundamental frequency.

The most serious evidence against the contention that pitch perception is a function of the presence of a high-amplitude fundamental comes from stimulus preparations in which the fundamental itself is not physically present. An example of such a preparation is a complex tone consisting of 600, 700, and 800 Hz. The pitch perception associated with the stimulus is that of the fundamental, 100 Hz. Helmholtz' interpretation of this finding was that the fundamental is introduced into the ear through nonlinear distortion; i.e. the perception of the fundamental is due to a combination or difference tone. This interpretation was in accord with Helmholtz' theory that the pitch of a stimulus was dependent upon a particular frequency causing a particular place on the basilar membrane to be activated.

The interpretation of Helmholtz was largely accepted (or unsuccessfully refuted by those who disagreed) until Schouten (1940) demonstrated that the fundamental of a complex was heard even when it was determined that no combination tone corresponding to the fundamental was produced. Later work by Licklider (1956), de Boer (1956) and others has confirmed this finding. Schouten hypothesized that the pitch of the fundamental was derived from the collective interaction of the poorly resolved upper harmonics on the basilar membrane; further, the pitch was assumed to be due to the time periodicity of the waveform. He termed this pitch the "residue" and supposed that the mechanism which determined the pitches of complex tones was sensitive to time cues rather than basilar membrane place cues.

Figure 1 gives a representation of the time cues to which the "pitch extractor" is assumed to be sensitive. The critical determiners of pitch are the temporal intervals between the waveform intensity peaks; in Figure 1 the ear is assumed to be sensitive to the temporal intervals 1 to 1', 2 to 2', and 3 to 3'. In residue pitch perception there is often an ambiguity--that is, more than one residue pitch may be perceived. By Schouten's theory this is accounted for when the pitch extractor picks time intervals such as 1 to 2', 1 to 3', etc. This sensitivity to time intervals between peaks within the envelope is often called sensitivity to "fine structure."

Since Schouten's study, residue pitch perception has received much attention and several alternate theories of residue pitch perception have been recently advanced. The most common factor among the theories is an attempt to explain how a multitude of spectral compositions come to result in one predominant pitch. For instance, three separate complex stimuli whose frequencies are 200, 400, and 600 Hz (complex A), 600, 800, and 1000 Hz (complex B), and 1800, 2000, and

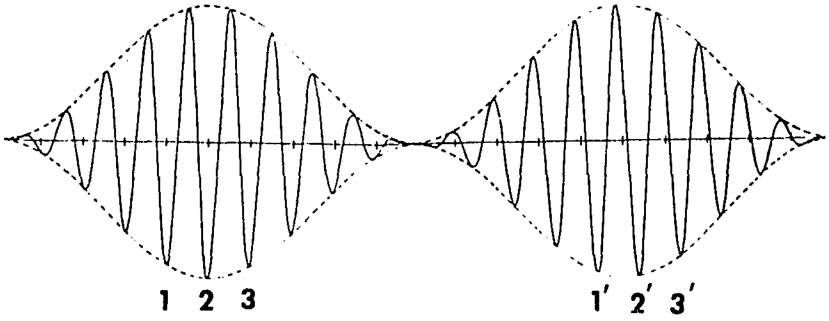

Figure 1. A diagram depicting the temporal intervals in a waveform to which a fine structure pitch extractor is assumed to be sensitive.

2200 Hz (complex C) all result in a residue pitch perception of 200 Hz. Schouten's residue theory rejected the place principle of pitch because (a) such components would not result in activity at the "200 Hz place" on the basilar membrane and (b) the periodicity seemed a much more likely pitch cue because each of the stimuli listed above has the same periodicity (characterized by a time envelope of 200 Hz). However, in residue pitch theory, place cues should not be discounted. A theoretical residue "pitch extractor" could integrate activity at particular places, such as those corresponding to frequencies of 600, 800, and 1000 Hz, or 1800, 2000, and 2200 Hz, and yield a pitch perception of 200 Hz. Thus, the simultaneous activation of several <u>places</u> could code a particular pitch.

Residue Pitch Theories

In an effort to account for the temporal factors which Schouten had indicated were important for residue pitch perception, Licklider (1951) proposed a temporally based autocorrelation model of pitch perception. In his model the temporal characteristics of each harmonic component were preserved by volleys of neural activity. Regularly repeating temporal events were then determined by a process of neural autocorrelation. The neural autocorrelation involved a transformation of frequency and phase-time information into a spatial (place) pitch code at some neural location higher than the level of the auditory nerve.

In a more recent treatment of residue pitch, Wightman (1973a; 1973b) found that the ear does not seem to be sensitive to the fine structure of the stimulus waveform as had been supposed by Schouten (1940), Licklider (1951), and others. Wightman manipulated the phase relations of complex tones, a technique which results in alterations of temporal fine structure, and found that such manipulations did not result in pitch changes. He concluded that temporal cues in general, and fine structure in particular were not important for pitch perception. Patterson (1974) and Bilsen (1973) also found residue pitch to be independent of phase, and therefore fine structure. Bilsen further reported that phase only affects residue pitch in that it may influence the intensities of combination tones. To complicate matters, however, Ritsma and Engel (1964) reported that phase or fine structure manipulation did change the value of the perceived residue pitch.

With the assumption that a pitch extractor is insensitive to temporal fine structure, Wightman (1973b) developed an autocorrelational model of pitch perception which was based on spectral rather than temporal information. In his model the spectral information analyzed at the cochlea undergoes a Fourier transformation (autocorrelation). In this process the spectral (place) information corresponds to the temporal dimension (τ) of autocorrelation. This temporal dimension represents autocorrelation delay time; the delay time that results in a maximum autocorrelation value is taken to determine the pitch of a complex tone. For instance, if the power spectrum of a 400, 600, and 800 Hz complex tone were Fourier transformed, a delay (τ) of 5 msec would result in a maximum autocorrelation value. The stimulus would then result in a pitch of 200 Hz (1/0.005). Pitch ambiguity would occur when there are two or more autocorrelation maxima.

Wightman's model is one of pattern transformation: the spatial pattern on the basilar membrane is transformed into a new pattern (a higher neural pattern) in which neural place represents the temporal dimension of autocorrelation. This place is activated by all stimuli that result in a maximum at the same autocorrelation delay time. Thus, a stimulus of 600, 800, and 1000 Hz and one of 1200, 1400, and 1600 Hz would activate different regions of the basilar membrane, but through Fourier transformation, would maximally activate an identical central place which represented the pitch associated with the stimuli (200 Hz). According to Wightman's theory, the central place is activated to a greater degree the more components there are in a stimulus, and the lower the components are in frequency (the better they are resolved). Thus several different patterns of activity on the basilar membrane can theoretically result in the activation of a single higher-neural place that corresponds to a single pitch.

Houtsma and Goldstein (1972) reported results which further weakened the original fine structure hypothesis of Schouten. In essence, they found that residue pitch could be perceived if a two-component complex stimulus were presented binaurally, one component to each ear. If a 600 Hz component were presented to the left ear and an 800 Hz component were presented to the right, a 200 Hz pitch would be perceived. Therefore, residue pitch perception would not seem to result from the collective temporal activity on the basilar membrane as Schouten had previously proposed. Instead, argued Houtsma and Goldstein, the coding of residue pitch must be more central than the basilar membrane or eighth nerve.

Goldstein (1973) later developed a model of residue pitch perception, taking the new binaural results into account. Briefly, he proposed that a central pitch extractor, or what he calls an "optimum processor" reads across a central tonotopically organized representation of harmonic components resolved at the cochleae. The individual components at each ear are represented as independent stochastic signals from which the maximum likelihood of the fundamental is estimated. As in Wightman's theory, stimulus fine structure is ignored, but Goldstein's model applies equally well based upon either peripheral place or time cues.

Hall and Soderquist (1975) have recently shown that residue pitch perception is more dependent upon the spectral information at each cochlea rather than the combined information from both cochleae. They showed that if one ear were given information that would result in a residue pitch of 200 Hz, and the other ear were given information which would result in a pitch of 400 Hz, both pitches were reported even when the combined information would have led to a perception of 200 Hz only. As an example, consider a complex stimulus of 800, 1200, and 1600 Hz presented to the left ear, and 1000, 1200, and 1400 Hz presented to the right ear.

If this information were simply transmitted to a central place and tonotopically laid out for pitch extraction, a single pitch of 200 Hz would be perceived. The results of Hall and Soderquist support Schouten's contention that peripheral information from each cochlea is important for residue pitch perception; however, Schouten's hypothesis concerning the importance of stimulus fine structure was not supported.

Finally, Terhardt's (1974) residue pitch theory should receive attention. Terhardt's theory is a nonmathematical pattern recognition theory. According to him, residue pitch is a learned perception. He supposes that the harmonics of a tone come to serve as cues for the perception of the fundamental. The more a listener hears a particular fundamental in the presence of its harmonics, the more strongly the harmonics become associated with the fundamental. Harmonics are cues for residue pitch, and the number of harmonics correlated with a particular fundamental determines pitch. For instance, if harmonics of 200, 300, 400, 500, 600, 700, and 800 Hz are present, there are seven cues for a pitch of 100 Hz, four for a pitch of 200 Hz, two for a pitch of 300 Hz and so on. The fundamental with the most cues is correlated with a neural site which is maximally activated;

in this example, the neural site would correspond to 100 Hz. Since there are also cues for other residue pitches, pitch ambiguity is accounted for.

At this point all residue theories suggest that residue pitch is somehow extracted from information at the cochlea. It is not clear yet to what extent residue perception may be a binaural phenomenon. Most theories seem to agree, however, that residue pitch is determined by the activation of a central neural extractor which is sensitive to many different peripheral patterns of activity.

Adaptation as a Tool for Psychophysical Investigation

A psychophysical method which has been recently used to reveal the neural organization of sensory systems has been that of adaptation. For instance, Blakemore and Campbell (1969) demonstrated the existence of visual "channels" tuned to specific spatial frequencies by using this method. Exposure to a particular spatial frequency (adaptation) was found to increase the absolute threshold for that frequency, and to frequencies nearly equal to that frequency, but not influence the threshold of more distant frequencies. Their conclusion was that the visual system may contain neurons selectively sensitive to particular spatial frequencies.

Similarly, in audition Kay and Matthews (1972) demonstrated selective adaptation to particular rates of relatively slow frequency modulation (FM). They showed that the sensitivity for detecting modulation in a stimulus declined as the rate of modulation in that stimulus approached the rate of a previously presented adaptation stimulus. The conclusion was that there are channels in the auditory system that are selectively tuned to particular rates of FM. In the Blakemore and Campbell and Kay and Matthews studies, the channels appeared to be central because threshold elevation was found in both eyes or ears when only one eye or ear was exposed to the adaptation stimulus.

Kay and Matthews (1972) and Green and Kay (1974) determined that there also seem to be channels selectively tuned to relatively slow, but not fast, rates of amplitude modulation (AM). It was also found that slow rate FM could adapt AM stimuli at the same rate, but that AM could not adapt FM. Since AM could not adapt FM, they concluded that the neurons selective to FM stimuli were sensitive to temporal frequency changes, since the AM and FM stimuli were similar in spectral content.

It is now suggested that relatively high rates of AM did not result in adaptation of AM or FM stimuli because subjects were not listening to the appropriate stimulus attribute. At slow rates of AM one hears a signal actually modulating in amplitude, becoming periodically louder and softer. For fast rates of AM, however, one does not actually hear amplitude modulating. What he hears, in fact, is <u>residue pitch</u>. For instance, if the rate of modulation of a 1000 Hz tone is 200 Hz (that is, the 1000 Hz tone modulates in intensity 200 times per second), one hears a residue pitch of 200 Hz. This is because AM generates a spectrum composed of the carrier frequency plus two other frequencies (sidebands) which are spaced from the carrier by the number of Hz of the modulating frequency. Thus a 1000 Hz tone modulated 200 times per second will yield a spectrum of 800, 1000, and 1200 Hz. The intensity of the sidebands is directly related to the depth of modulation or intensity of the modulation frequency--100% depth yields sidebands that are 6 dB less intense than the carrier. Lesser percent depth yields less intense sidebands. When the percent of modulation is lowered beyond a certain point, residue pitch is no longer perceived, presumably because the sidebands are not intense enough to be cues for residue pitch perception. An FM signal also generates sidebands that are spaced equal to the rate of modulation. However, the phase relations differ from those in AM, and a variable number of sidebands can be produced. However, AM and FM stimuli can be generated which have essential differences only in temporal fine structure, with the spectrum identical.

Informal reports have indicated that fast rate AM tones can result in adaptation of other AM tones if the criterion for the listener's threshold is shifted from "just noticeable amplitude fluctuations" to "just noticeable residue pitch." In the former case the percent of AM in a "test" tone is raised until one hears amplitude changing after exposure to an 100% AM adaptation tone; in the latter case, the percent of AM in a "test" tone is raised until residue pitch is just heard after exposure to an adapting stimulus of 100% AM. Both cases involve the adaptation of a particular AM rate by an adaptation tone. However, in the former case, the auditory system would appear to be adapting to the temporal aspect of the stimulus, while in the latter, the spectral cues probably become important. Thus for fast rate AM, adaptation should not be considered to be directly related to amplitude modulation; instead it is probably related to spectral composition. Amplitude modulation is simply a means of generating a signal which has a complex spectrum of variable composition.

It is suggested that adaptation of residue pitch may be an important tool for the investigation of residue pitch for several reasons. First, if it can be demonstrated that a 100% AM tone raises the threshold for the detection of residue pitch for AM tones modulated at identical or near identical rates, but not to greatly different rates, channels selective to particular residue pitches can be demonstrated. Second, several assumptions concerning residue pitch theories can be subjected to empirical tests. For instance, if several different patterns on the basilar membrane activate the same central pitch extractor, adaptation with one peripheral pattern should increase the detection threshold for another pattern. Specifically, adaptation with a 100% AM tone of 600, 800, and 1000 Hz should increase the threshold for the residue pitch perception of a 1600, 1800, and 2000 Hz stimulus, even though the stimuli activate different peripheral areas.

Thirdly, the problem of whether residue pitch is more dependent upon peripheral cues (each ear, independently) or central cues (combined peripheral information from both ears) can also be subjected to investigation. The AM adaptation tones can be presented to one ear, while a test stimulus can be presented to the other ear to determine the extent, if any, of binaural adaptation. Pitch ambiguity can also be investigated with the adaptation method, as described in the next section.

Finally, the contention has been made that at high rates of modulation the ear is sensitive only to spectral factors. It is known that high-rate FM and AM stimuli can be generated to yield identical residue pitch, and have identical spectra (disregarding phase). If a pitch extractor is sensitive to spectra, then, and not to phase and temporal factors, high-rate AM and FM should adapt each other equally. (Note that this has <u>not</u> been found to be the case for slow AM and FM.)

CHAPTER II

THE EXPERIMENTS

Apparatus

The apparatus consisted of a sound attenuated room, Phillips PM5168 function generator, Interstate Electronics F-35 function generator, Sony TC-280 tape deck, a potentiometer with which Ss could adjust amount of modulation, and calibrated TDH 39 earphones (circumaural muffs) by which stimuli were presented. Intensities of stimuli were monitored on a Tektronix 514N waveform analyzer and a 320-A Ballantine True RMS voltmeter. Frequencies were monitored by a Hewlett-Packard 5221B electric counter.

Subjects and Training

Three subjects with normal hearing were used. All had some degree of musical training, and could readily hear and match residue pitch. A fourth S, who could not readily hear the residue, was dropped from the study. Absolute thresholds were determined for each stimulus used in the experiment.

All Ss were trained to identify residue pitch so that all would attend to the same psychological attribute when listening to the stimuli. Specifically, Ss were asked to match the pitch of an adjustable square wave to that of a particular residue pitch. The S was said to be attending to residue pitch when he consistently matched the square wave pitch to that of the residue pitch. One hour per S was used for this training. All Ss were also given training in tracking the threshold for residue pitch by raising and lowering percent of AM modulation with a potentiometer. This training was given to the Ss approximately 15 minutes each during the training session, and about 5 minutes before each experimental session.

General Procedure

After training was completed each S was seated in the sound attenuated chamber and the experimental sessions were begun. All stimuli were presented at 30 dB SL, an intensity low enough to minimize the effects of combination tones.

The general procedure was in two phases for each subject. In phase I the S's threshold for residue pitch perception with an AM signal was determined. The question of interest was the minimum amount of AM modulation necessary to elicit the perception of a residue pitch. The minimum amount of modulation (measured in dB of sidebands) required to perceive the residue was defined as the unadapted threshold. This threshold value was then used as a baseline to determine the amount of threshold shift in a _test stimulus_ or _test pitch_ caused by an _adaptation stimulus_ or _adaptation pitch_ presented in Phase II. The spectrum and ear of presentation of the test stimuli and the stimuli used to obtain unadapted thresholds were always identical.

In both phases of data collection the _S_'s task was the same: adjust the potentiometer to the value which just elicits the residue pitch. The potentiometer directly affected the amount of modulation of the carrier sinewave from 0% to 100% and thus, the psychophysical technique was similar to the classical method of adjustment. Errors of habituation and anticipation were minimized by the experimenter's control of the initial modulation value. The initial value varied, but was always more than 10 dB below residue pitch threshold. The _S_ always had three opportunities per trial to adjust the amount of modulation in the test stimulus. The first two adjustments occurred within 5-second periods. The last adjustment of a trial, a final "touching-up" of the previous two, was accomplished in 3 seconds. Between each stimulus or test stimulus adjustment, a 5-second period of silence (for the Phase I, _unadapted threshold_) occurred, or a 5-second period of adaptation stimulus (for the Phase II, _adapted threshold_ portion) occurred. Figure 2A shows a typical trial for the Phase I unadapted threshold. The intensity of the modulation (sidebands of the AM stimulus) was recorded following the last 3-second adjustment. The S's thresholds (unadapted and adapted) were based on the average of six trials, and the trials were spaced by at least two minutes to prevent fatigue.

Figure 2B shows a typical trial for the adaptation portion of the study (Phase II). The significant differences in procedure are the 30-second adaptation stimulus presented prior to the S's test stimulus adjustment, and the presentation of the adaptation stimulus during the previously silent intervals. The adaptation stimulus was always a 100% AM signal and was recorded on tape for presentation at the appropriate time.

There were both monaural and binaural conditions. In monaural conditions, the adaptation and test tones were both presented to the right ear. In the binaural conditions, the adaptation tone was presented to the left ear, while the test stimulus was presented to the right ear.

Adaptation was said to occur if the threshold of the test stimulus (adapted threshold) were higher than that of

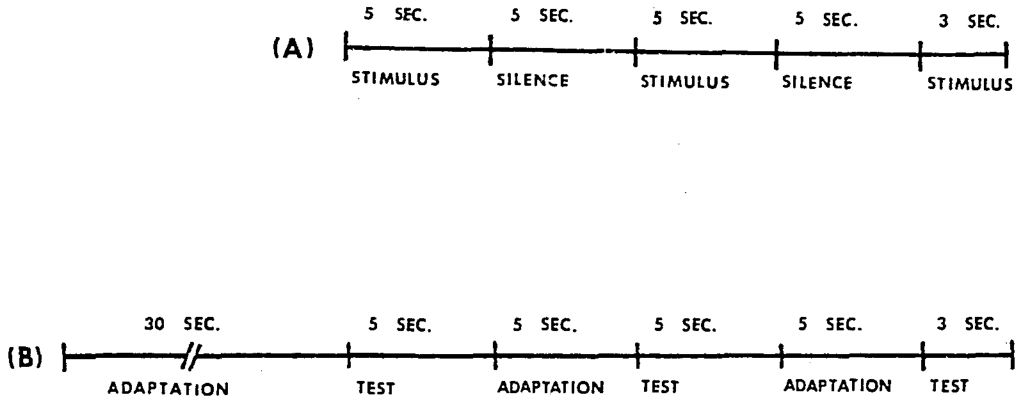

Figure 2(A). A diagram indicating the temporal presentation of the unadapted threshold stimulus. (B). A diagram indicating the temporal presentation of the adaptation and test stimuli.

the unadapted threshold. The degree of adaptation was equal to the dB level of the adapted threshold minus the value of the unadapted threshold. These were measures of the intensities of AM sidebands.

Subjects were run in daily two-hour sessions, in blocks of six trials. There were three-minute rest periods between blocks.

Specific Procedure

Experiment 1: Channels for Residue Pitch

The first experiment consisted of two investigations of the hypothesis that there are channels in the auditory system specifically tuned to particular residue pitch values. In the first investigation the 3rd, 4th, and 5th harmonics of 200 Hz were used as the test and unadapted threshold stimulus. An 800 Hz tone was the carrier and 600 and 1000 Hz were the sidebands. The adaptation stimuli were the 3rd, 4th, and 5th harmonics of 184, 188, 192, 196, 200, 204, 208, 212, and 216 Hz. It was hypothesized that adaptation stimuli closest in pitch to the test stimulus would suffer the greatest threshold elevation if specific channels existed. The test stimuli were presented in a random order for each S. The second investigation repeated the procedure with the 9th,10th, and 11th harmonics of 200 Hz as the test and unadapted threshold stimuli to determine whether channel specificity was constant over different spectral regions. The adaptation stimuli were 9th, 10th, and 11th harmonics of 168, 176, 184, 192, 200, 208, 216, 224, and 232 Hz. The adaptation stimuli for the higher spectral region differed from those of the lower region because pilot data indicated that a broader range of frequencies might result in adaptation in the higher spectral region. Since aural resolution is not as fine for high frequencies, lower frequencies were expected to have more specific channels than higher frequencies.

Experiment 2: Adaptation by Spatially Separate Peripheral Patterns

This experiment tested the hypothesis that different patterns on the basilar membrane, which are spatially separated, may adapt each other because they adapt a common central pitch extractor. To test this, the 3rd, 4th and 5th harmonics of 200 Hz were used as the test and unadapted threshold stimuli. The adaptation stimuli were the 9th, 10th, and 11th harmonics of 168, 176, 184, 192, 200, 208, 216, 224, and 232 Hz. The experiment was repeated with the 9th, 10th and 11th harmonics of 200 Hz serving as the test and unadapted threshold stimuli and the 3rd, 4th and 5th harmonics of 184, 188, 192, 196, 200, 204, 208, 212, and 216 Hz serving as the adaptation stimuli. It was expected that the lower spectral region would result in greater adaptation than would the upper region stimuli. This is predicted by Wightman's theory because low spectral signals result in a greater amount of activity at the central neural place which corresponds to residue pitch. Terhardt's model would also predict this result since a particular fundamental will be correlated more highly with its lower harmonics than its upper harmonics. This is because lower harmonics are more likely to be present in speech and musical sounds than upper harmonics.

Experiment 3: Components as "Cues" for Pitch: Pitch Ambiguity

The hypothesis that the components of a stimulus may adapt several residue pitches was examined. This experiment also yielded data relevant to residue pitch ambiguity. The components 800-1000-1200 Hz were used as an adaptation tone. In Terhardt's terms this had three "cues" for 200 Hz, two "cues" for 400 Hz and one "cue" for 300 Hz. The test stimuli were 800 - 1000 - 1200 Hz for 200 Hz residue; 800-1200 - 1600 Hz for 400 Hz residue; 600 - 900 - 1200 Hz for 300 Hz residue. The relative degree of adaptation was compared for all stimuli. The stimuli with more pitch "cues" were expected to suffer greatest adaptation. The experiment was repeated with 600-800-1000 Hz as the adaptation stimulus. This stimulus had only one cue for 400 Hz and one for 300 Hz.

It may be that components which can give rise to residue pitch perception must be represented in the cochlea in order for adaptation to occur. Since the adaptation stimulus can not give rise to a 300 Hz residue because it contains only one "cue" for that pitch (1200 Hz), it may not adapt the 300 Hz residue test stimulus. Similarly, the 600-800-1000 Hz stimulus contained only one "cue" for 400 Hz and 400 Hz adaptation may not occur for the same reason. If no adaptation for the 300 or 400 Hz residue test stimulus is demonstrated, then the hypothesis that peripheral "cues" activate a central pitch extractor may require modification.

To investigate this line of thought further, another investigation was done with a stimulus containing three cues for a 200 Hz residue. The spectral spacing was large enough to prohibit residue pitch perception. These "cues" were 400-1400-2400 Hz, and served as the adaptation stimulus. The test stimulus was 800-1000-1200 Hz, a stimulus which gives rise to a residue pitch of 200 Hz. If peripheral "cues" are assumed to be adequate to activate a central pitch extractor, then adaptation would be expected. In contrast, if the cues must cause an actual perception of residue pitch, no adaptation would be expected.

Experiment 4: A Contrast of Fast Rate AM and FM Stimuli

It has been suggested that, at high rates of AM or FM, the auditory system is sensitive to spectral cues , but not temporal fine structure cues. Therefore, this experiment examined the hypothesis that high rate AM and FM stimuli adapt each other equally. The adaptation stimulus was an AM signal of 400-600-800 Hz. The test stimulus consisted of the same components but was approximately FM (QFM). The QFM tone was generated by shifting the carrier of an AM tone by 90°. This phase shift results in a QFM waveform with the same spectrum as AM, but with different fine structure. The experiment was repeated using QFM as the adaptation stimulus and AM as the test stimulus. Experiments measuring AM adapting AM stimuli, and QFM adapting QFM were also performed with 400, 600, and 800 Hz spectra.

Experiment 5: A Comparison of Pure Tone and Residue Pitch

All of the experiments have been based upon the premise that residue pitch causes selective adaptation in the auditory system. Accept for a moment the assumption that all stimuli which give rise to 200 Hz residue activate a central 200 Hz pitch extractor. Since, by definition, the extractor is sensitive to 200 Hz, it would be interesting to see if a 200 Hz pure tone would result in residue pitch adaptation. If it does not, it must be assumed that pure tone pitch and residue pitch are extracted by different mechanisms. This question was examined by using a pure tone of 200 Hz and 30 dB SL as the adaptation stimulus. The test stimulus was an AM complex of 600-800-1000 Hz.

Experiments 1-5 were repeated, with the adaptation stimulus being presented to the left ear, and the test stimulus being presented to the right.

Experiment 6: Duration of Time for Adaptation and Recovery from Adaptation

Finally, experiments were done which examined the amount of time needed to cause "complete" adaptation and the amount of time to recover from adaptation. A 600-800-1000 Hz tone was used as an adaptation stimulus and test stimulus. The degree of adaptation was noted both with regard to (a) various durations of adaptation stimulus presentation, and (b) various periods of silence after the adaptation stimulus.

CHAPTER III

RESULTS

The results of the experiments will be presented in the order initiated in the procedure section. The data points in the figures will represent an average of the six trials that made up a condition. The data will be discussed in the following chapter.

Experiment 1

The results of experiment 1 (residue pitch - specific channels) are summarized in Figures 3,4,and 5. The values on the horizontal axis represent the fundamental (f_o) of the adaptation stimulus. The test stimulus always had a residue pitch of 200 Hz. Each figure displays data for one of the three Ss. Several points should be noted in regard to the data on pitch - specific channels. First, for all data, both monaural and binaural, low and high spectral region, strongest adaptation occurred when the adapting fundamental pitch (f_o) was equal to the test pitch; as the adapting pitch became more and more disparate from the test pitch, the degree of adaptation fell rapidly. Second, the channels for the lower spectral region (3rd, 4th, and 5th

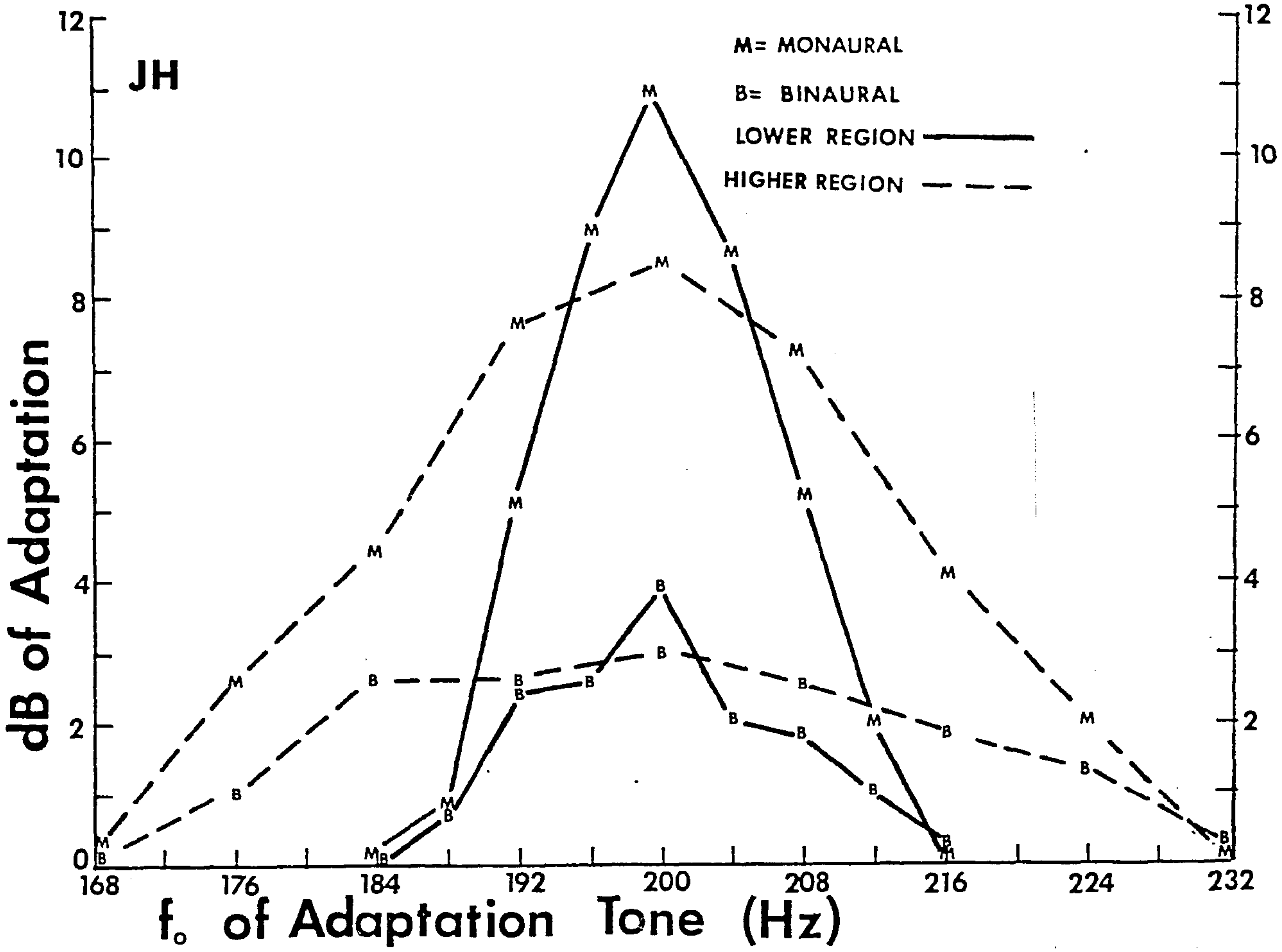

Figure 3. Adaptation curves from experiment 1 for subject JH. Monaural and binaural data showing degree of adaptation of a 200 Hz residue test stimulus.

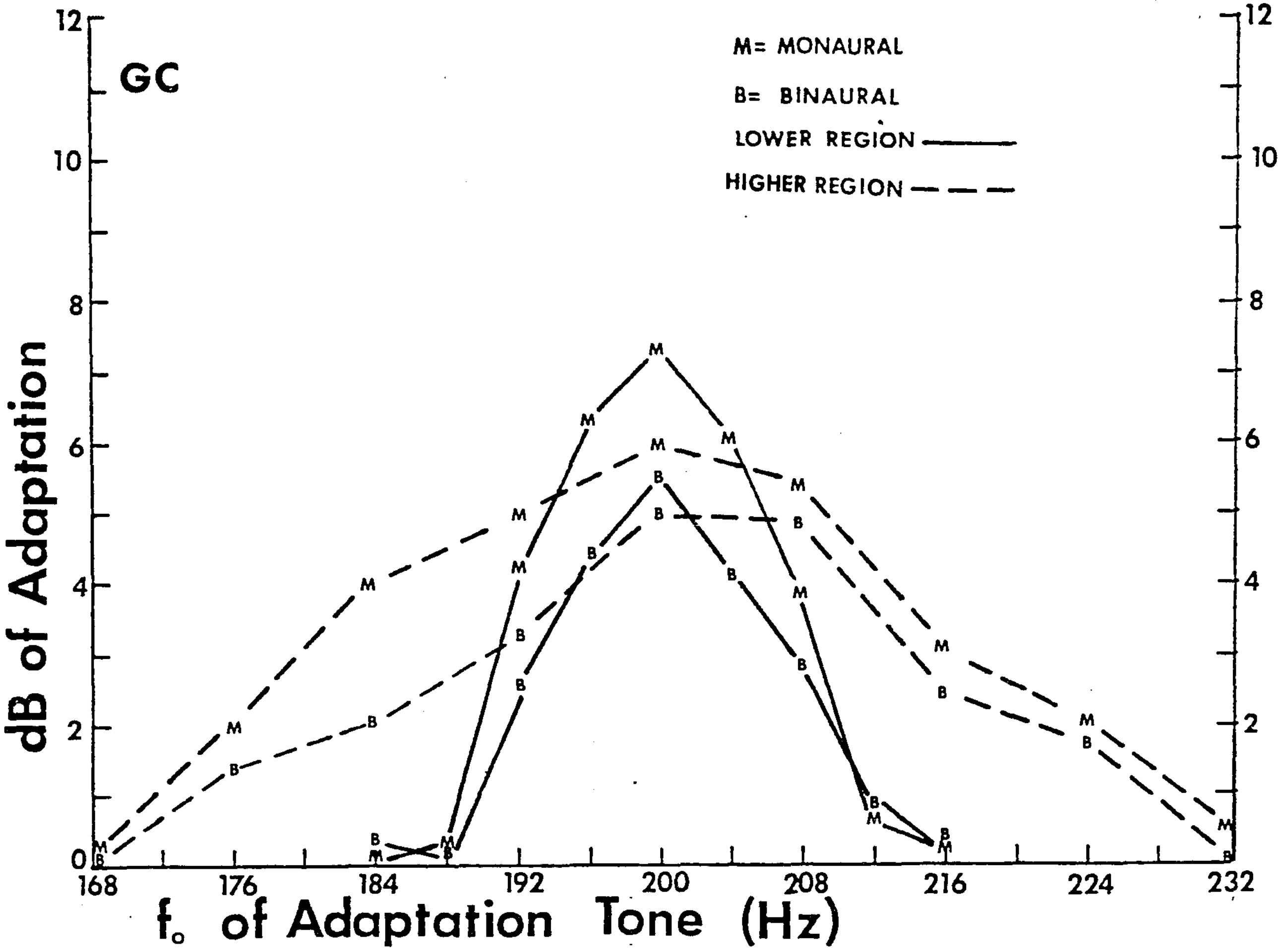

Figure 4. Adaptation curves from experiment 1 for subject GC.

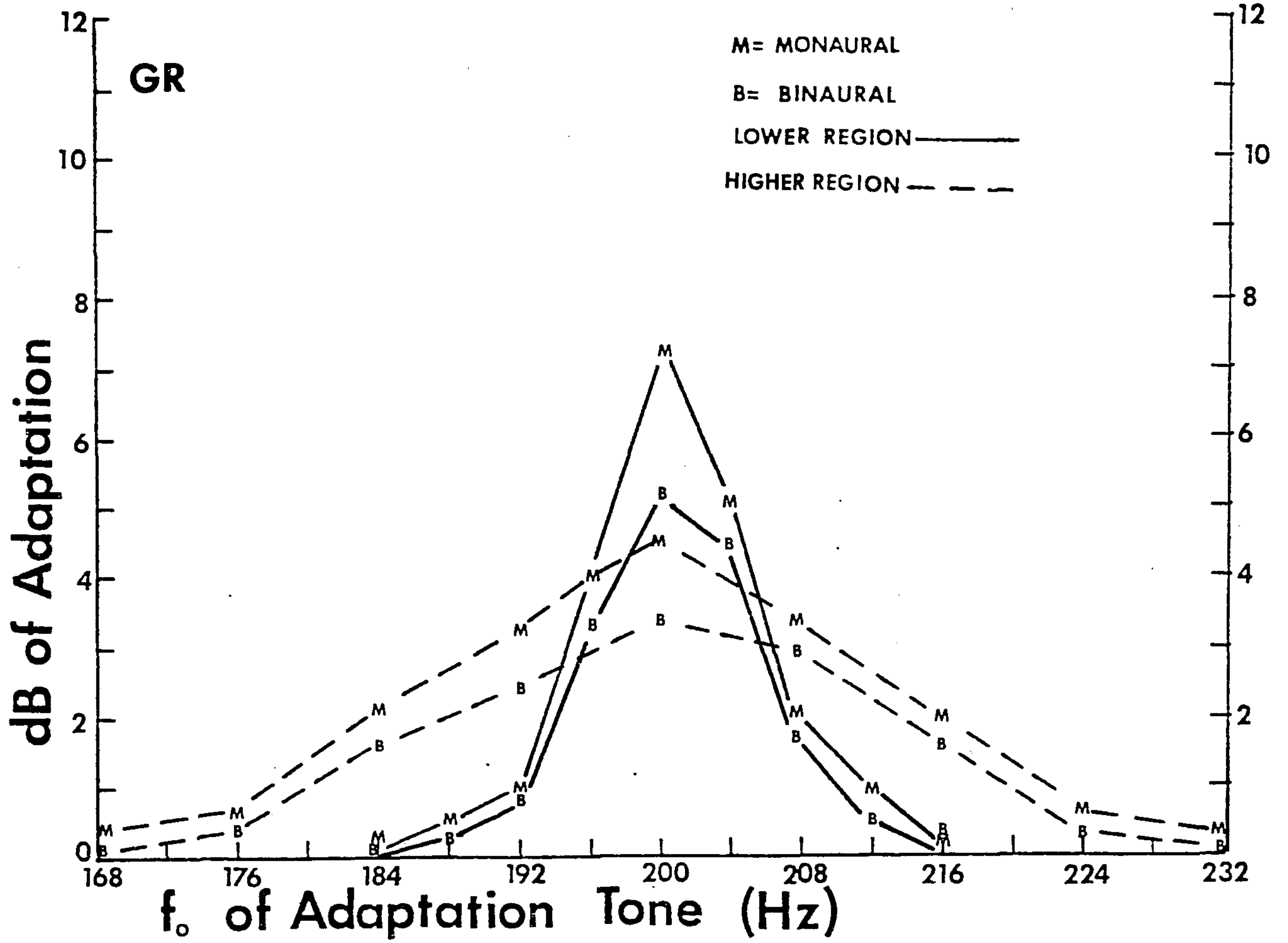

Figure 5. Adaptation curves from experiment 1 for subject GR.

harmonics) appear to be narrower or more pitch-specific than those for the higher region (9th, 10th, and 11th harmonics). For the lower region the channel width ranged from approximately 184 to 216 Hz. That is, adaptation of a 200 Hz test stimulus resulted when the adaptation stimulus was from 184 to 216 Hz. In contrast, when the adaptation and test stimuli were in the higher region, adaptation ranged from about 168 to 232 Hz for a 200 Hz test stimulus. This broadening of pitch-specific channels for higher spectral region occurred in both monaural and binuaral conditions.

Third, the degree of adaptation in binaural conditions was consistently less than that in corresponding monaural conditions. For subject JH the differences between monaural and binaural conditions are relatively great (as much as about 7 dB), while subjects GR and GC show smaller,but consistent, differences. For all Ss the differences between monaural and binaural conditions were greatest when the adaptation pitch equalled the test pitch, and became less when the adaptation and test pitches were not equal. Thus, the binaural adaptation curves are flatter, while the monaural curves are relatively steeper.

Fourth, all Ss seemed to demonstrate approximately the same channel specificity among all conditions, but there were individual differences in degree of adaptation. For instance, the maximum degree of adaptation for the monaural, lower region condition ranged from about 11 dB for JH to about 7 dB for GC; the maximum degree of adaptation for the binaural, lower region condition ranged from about 5.5 dB for GC to about 4 dB for JH. Fifth, the maximum degree of adaptation in the lower region was consistently greater than that for the upper region.

For a particular point in the figures the values which made up the average were nearly identical, rarely differing from each other by more than a loudness JND (just noticeable difference). The standard deviation of the values contributing to a data point never exceeded 0.7 dB. This precision is thought to be due in part to the training of the Ss, and in part to the nature of the task.

Experiment 2

The results of experiment 2 (adaptation by spatially separate peripheral patterns) are summarized in Figures 6,7 and 8. The pitch values on the horizontal axis represent adaptation stimuli. The test stimulus always had a residue pitch of 200 Hz. The most striking finding was

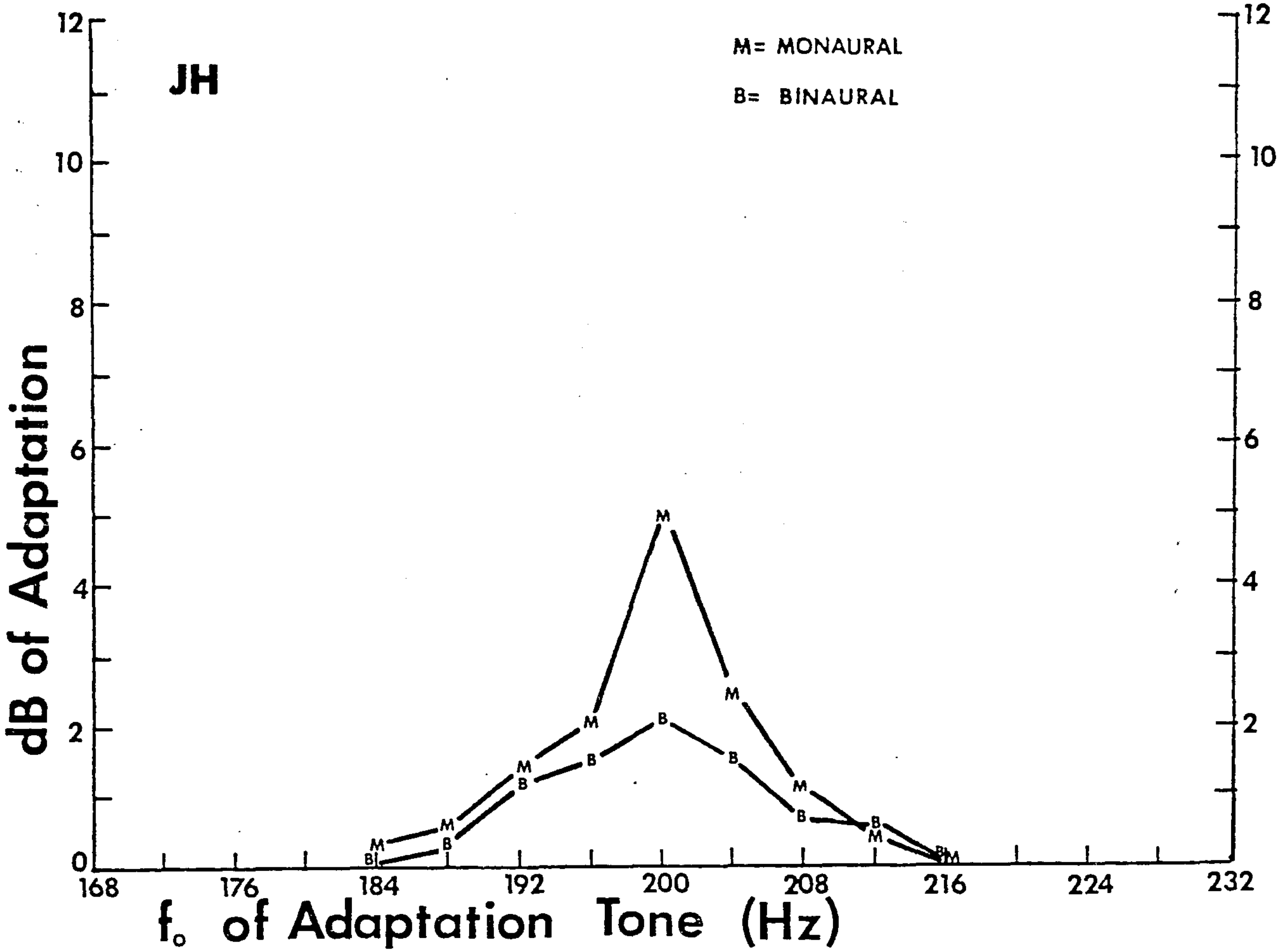

Figure 6. Adaptation curves from experiment 2 for subject JH. Data is only for low region adapting a high region test tone.

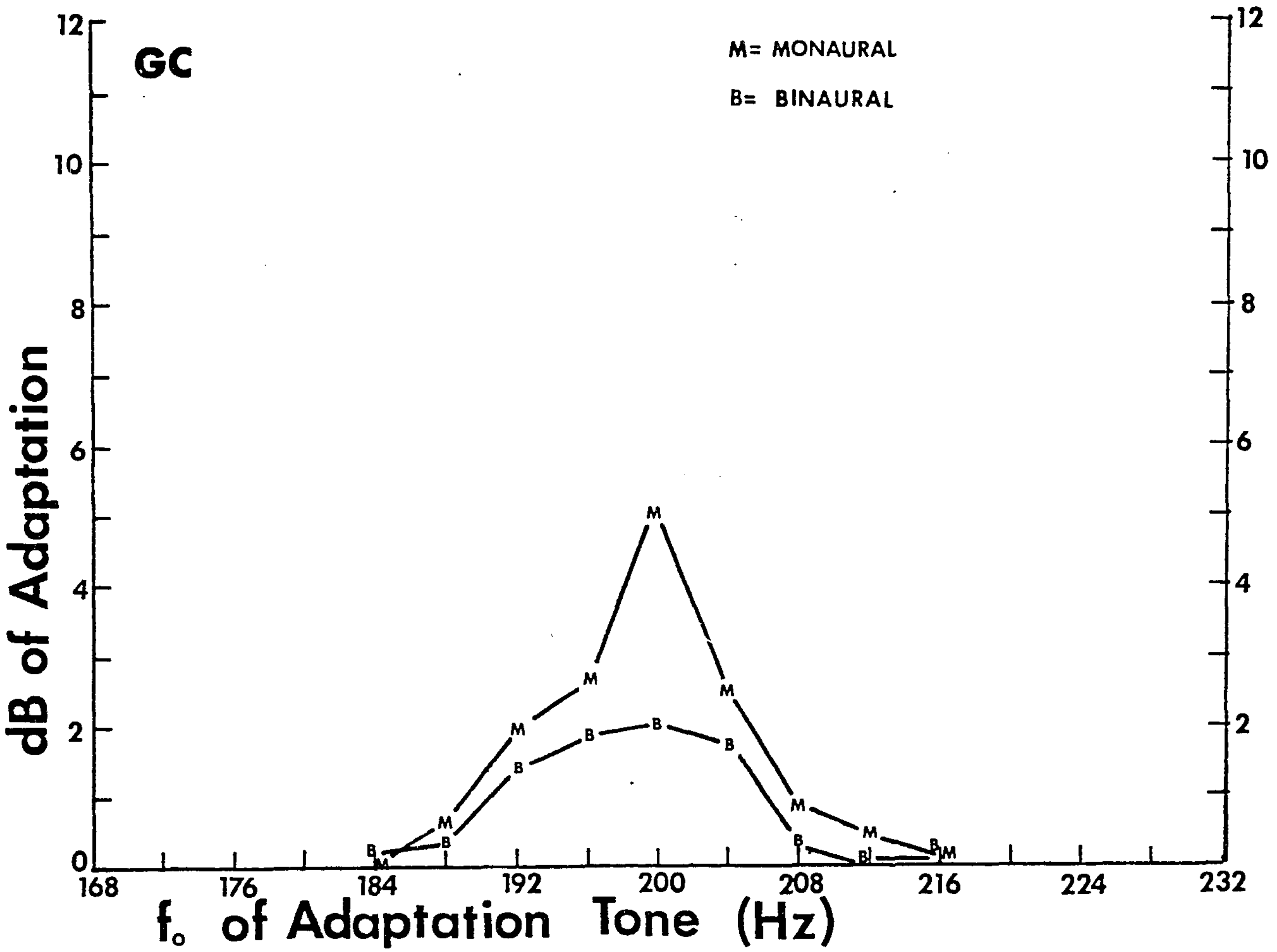

Figure 7. Adaptation curves from experiment 2 for subject GC.

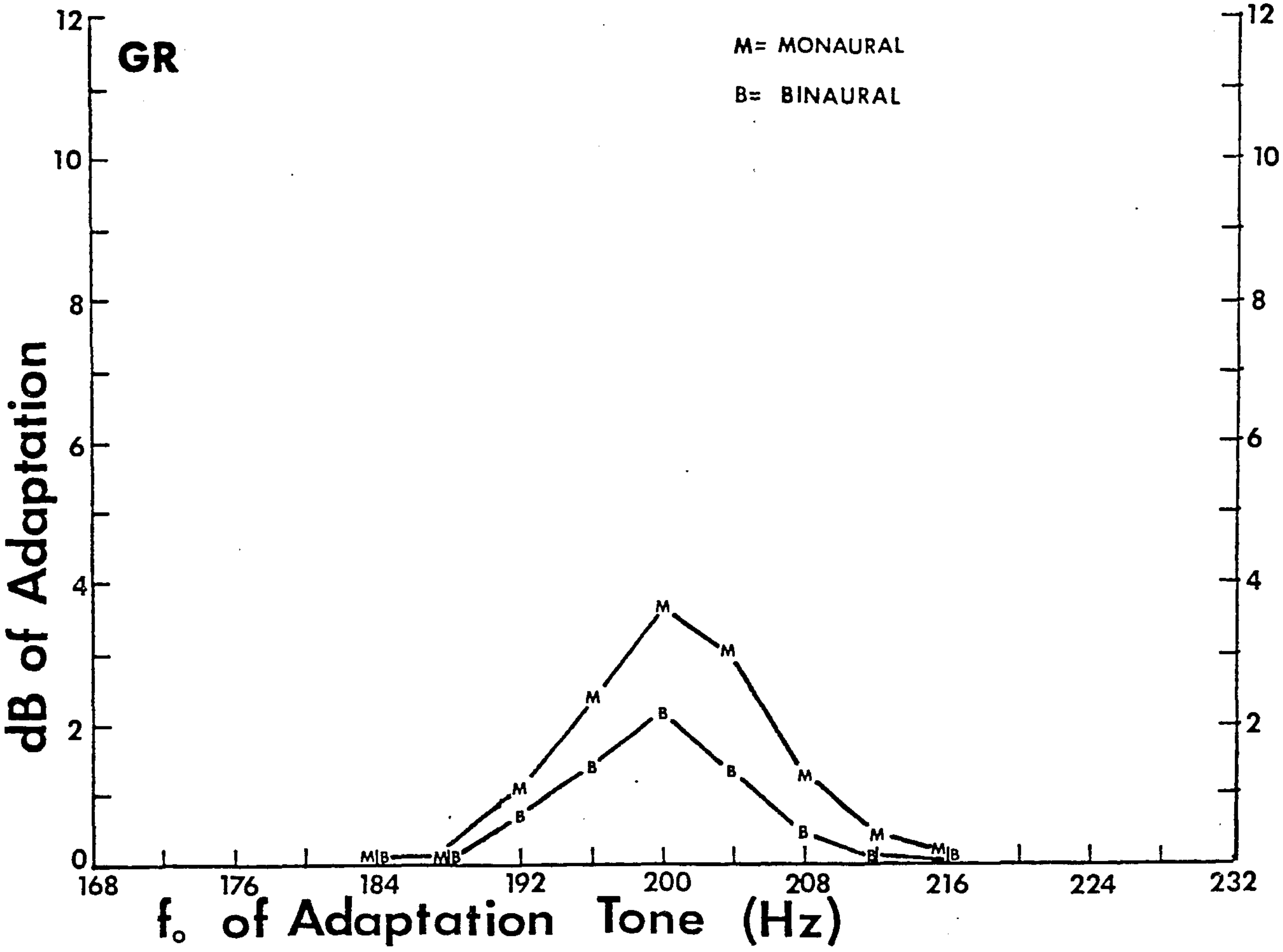

Figure 8. Adaptation curves from experiment 2 for subject GR.

the adaptation pitches of the lower region resulted in adaptation of the upper region 200 Hz pitch, while adaptation pitches in the upper region resulted in no corresponding adaptation of the lower region 200 Hz pitch. Thus, in Figures 6-8 the data points represent pitches from the low spectral region adapting a residue pitch of 200 Hz which arose from a high spectral region (the 9th, 10th and 11th harmonics of 200 Hz). As can be seen the range of pitches which caused adaptation is again from about 184 to 216 Hz. Figures 3-5 with 6-8 show that the degree of adaptation resulting from a high spectral adapting pitch is slightly greater than that resulting from a low spectral adapting pitch when the 200 Hz test pitch is from the higher region. This is true both monaurally and binaurally. Again, the monaural adaptation is consistently greater in degree than binaural adaptation; binaural adaptation is again, relatively flatter, as depicted in the adaptation curves.

In summary, the low residue pitches seem to adapt the 200 Hz residue pitch from the higher spectral region in much the same way as high residue pitches; the degree of adaptation is slightly less when low region pitches adapt a high region pitch, but the form of the adaptation curves are similar. No adaptation at all occurs when high region pitches are used to attempt the adaptation of a low region pitch.

Experiment 3

The results of experiment 3 (components as "cues" for pitch: pitch ambiguity) are summarized in Table 1. Adaptation values which did not exceed a loudness JND were not listed in the table. As can be seen, when the adaptation stimulus was 600-800-1000 Hz, only a pitch of 200 Hz suffered adaptation; neither test pitches of 300 Hz or 400 Hz were adapted. When the adaptation stimulus was 800-1000-1200 Hz, however, both test pitches of 200 Hz and, to a lesser extent 400 Hz, were adapted; a test pitch of 300 Hz remained unadapted. These results were found both monaurally and binaurally. When adaptation occurred, it was stronger for monaural than for binaural conditions. It was stronger for a pitch of 200 Hz than for 400 Hz. When the adaptation stimulus was 400-1400-2400 Hz, there was not adaptation of a 200 Hz test pitch. Thus, it is clear that in order for adaptation of a pitch to take place, there must exist in the stimulus at least <u>two</u> cues for the residue pitch, and the cues must be consecutive harmonics. Another way of describing this result is that the adapting stimulus

TABLE 1

ADAPTATION OF 200, 300, AND 400 HZ RESIDUE PITCHES BY 200 HZ RESIDUE ADAPTATION TONES

	Adaptation = 600-800-1000 Hz				Adaptation=800-1000-1200 Hz			
		dB ADAPTATION				dB ADAPTATION		
	Test Tone (Hz)	JH	GC	GR	Test Tone (Hz)	JH	GC	GR
MONAURAL	600-800-1000 (200 HZ RESIDUE)	10.1	9.0	7.3	800-1000-1200 (200 HZ RESIDUE)	9.3	9.3	7.7
	600-900-1200 (300 HZ RESIDUE)	—	—	—	600-900-1200 (300 HZ RESIDUE)	—	—	—
	800-1200-1600 (400 HZ RESIDUE)	—	—	—	800-1200-1600 (400 HZ RESIDUE)	5.8	5.1	4.4
BINAURAL	600-800-1000 (200 HZ RESIDUE)	4.3	3.8	4.2	800-1000-1200 (200 HZ RESIDUE)	4.0	4.3	3.6
	600-900-1200 (300 HZ RESIDUE)	—	—	—	600-900-1200 (300 HZ RESIDUE)	—	—	—
	800-1200-1600 (400 HZ RESIDUE)	—	—	—	800-1200-1600 (400 HZ RESIDUE)	2.9	2.5	2.2

must contain components which can give rise to the perception of a residue pitch, in order for that residue pitch to suffer adaptation.

Experiment 4

The results of experiment 4 (pitch comparison of fast-rate AM and FM stimuli) are easily summarized. For all Ss an AM adaptation stimulus of 400-600-800 Hz adapted the 200 Hz residue pitch of a 400-600-800 Hz QFM test pitch by an average of about 10 dB monaurally and about 5 dB binarually. The QFM adaptation stimulus with the same spectrum resulted in identical adaptation when the AM tone was used as the test stimulus. Further, the same amount of adaptation resulted when the AM tone was used to adapt an AM test stimulus, and when a QFM tone was used to adapt a QFM test stimulus. Thus, adaptation data indicate that AM and QFM stimuli cause equal effects on the auditory system, when the spectra of the stimuli are equal.

Experiment 5

The results of experiment 5 (comparison of pure tone and residue pitch) showed that a pure tone of 200 Hz does not adapt a residue pitch of 200 Hz (components 600-800-1000 Hz), either monaurally or binaurally.

Experiment 6

Informal observations had previously indicated that 30 seconds of adaptation was sufficient for adaptation, and that a two-minute rest period was sufficient for recovery from adaptation. These assumptions were systematically examined with two of the Ss. To determine the duration required for maximum adaptation, an adaptation tone of 600-800-1000 Hz was used to adapt a test tone of 600-800-1000 Hz. The level of adaptation was measured after durations of 7, 15, 30, and 60 seconds. As Figure 9 indicates, degree of adaptation approached asymptote after 30 seconds for both Ss. The time necessary to return to unadapted threshold after 30 seconds of adaptation was also determined. Recovery from adaptation was measured after 0, 10, 30, and 60 seconds of silence. As Figure 10 indicates, both Ss had almost recovered from adaptation after approximately 30 seconds. Figures 9 and 10 essentially suggest that adaptation for residue pitch is rapid and that recovery from adaptation is likewise rapid. Adaptation and recovery from adaptation also seem temporally symetrical.

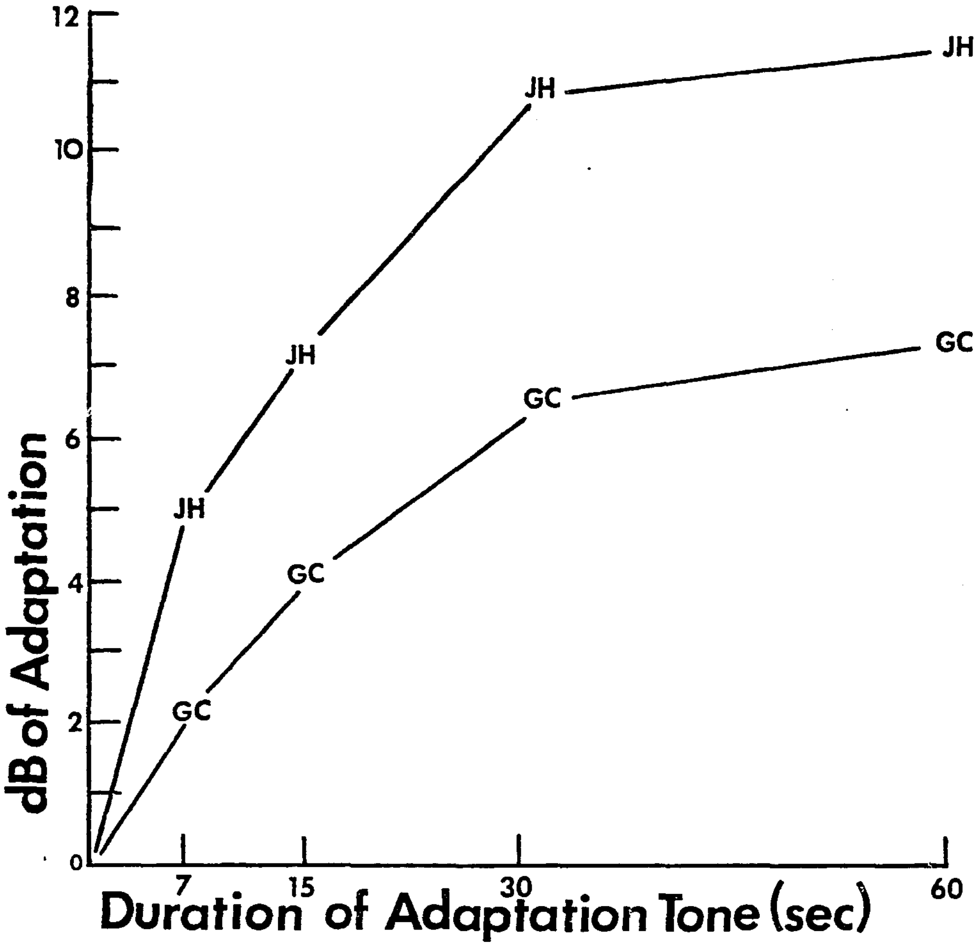

Figure 9. Degree of adaptation as a function of time for subjects JH and GC. Adaptation was complete after about 30 seconds.

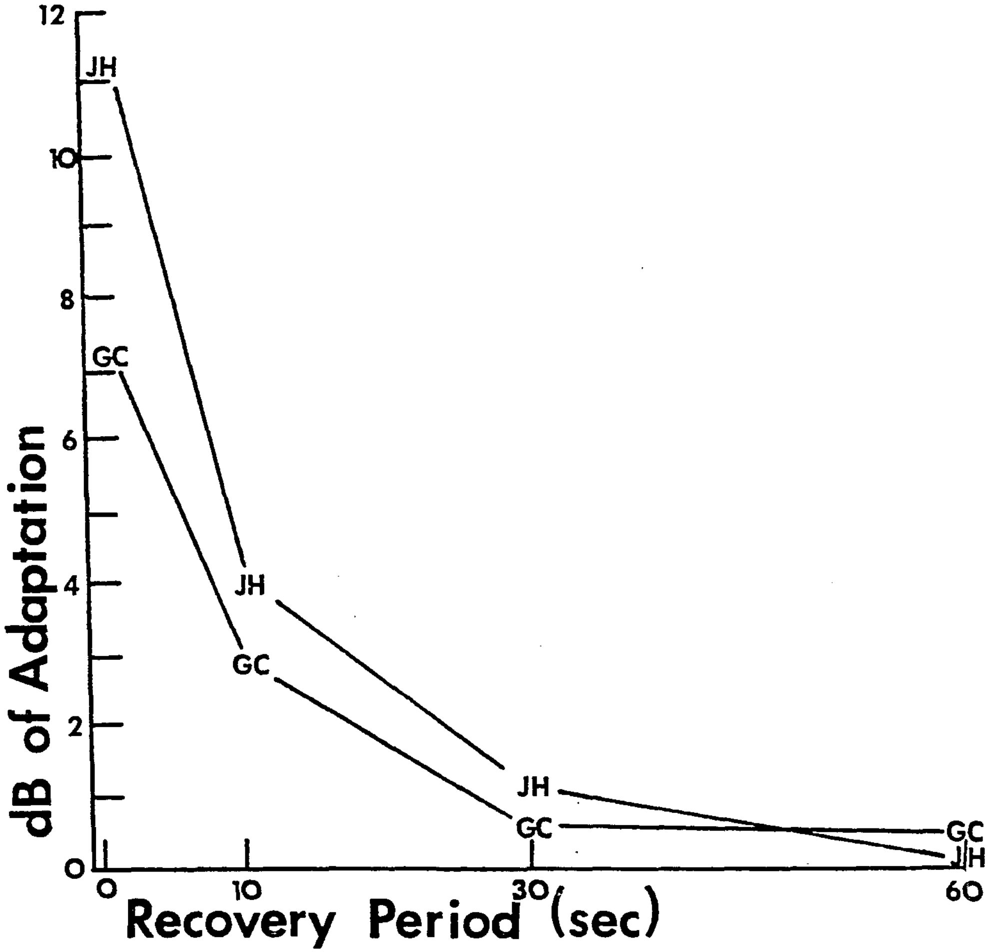

Figure 10. Recovery from adaptation as a function of time. Recovery was complete after about 30 seconds.

CHAPTER IV

DISCUSSION

It is clear that the experiments described here offer strong psychophysical evidence for the existence of auditory channels selective for residue pitch. The evidence augments the understanding of pitch perception, and suggests additional refinements in the pitch perception models which have been proposed.

Evidence for Specialized Pitch Extraction

The data have indicated that adaptation is strongest when the residue pitch of the adaptation stimulus equals that of the test stimulus, when the tones are presented to the same ear, and when the tones have equal spectral composition. A possible explanation for these results is that the adaptation may be due to simple fatigue of the receptors. This is not likely, however, since the stimuli were always presented at low sensation levels (30 dB), and were presented for only brief periods of time. The fact that a 600-800-1000 Hz complex maximally adapts residue generated by the same complex may imply that the adaptation was caused by stimulation at the frequencies of 600, 800, and 1000 Hz, and was not directly related to the residue pitch of 200 Hz. This possibility may be examined if a simple experiment is performed. When white noise is shaped into a narrow band with a center frequency of 800 Hz and the bandwidth extending slightly beyond 600 and 1000 Hz this stimulus can be used as an adaptation stimulus for a test stimulus of 600-800-1000 Hz. When this is done, there is absolutely <u>no</u> adaptation of the 200 Hz residue pitch by the shaped noise (monaural presentation). Thus, the adaptation with the spectrally similar stimuli is not due to the adaptation of neurons sensitive to a particular frequency region. Rather, the adaptation mechanism must be sensitive to the harmonic relations among the stimulus components.

Most of the models that have been proposed for residue pitch describe neural structures that extract the pitch of complex stimuli. For example, a pitch extractor for 200 Hz is activated when peripheral information containing harmonics of 200 Hz is presented in one ear or the other, be it of low or high spectral composition. While this view of a generalized 200 Hz pitch extractor receives some support from the data reported here, the data more compellingly call for a view which emphasizes the existence of several specialized pitch extractors (neural structures) for a particular pitch. Each of these structures would be differentially excited depending on the nature of the peripheral stimulus.

The data indicate that there may well be such specialized pitch extractors: one pitch extractor may be maximally sensitive to left-ear stimulation by low-spectral components of 200 Hz fundamental; another maximally sensitive to right ear stimulation by high-spectral components, etc. What is important to note, however, is that these specialized pitch extractors or channels are not completely independent; for the data clearly show that a stimulus at one ear can adapt that presented to another, and that pitch derived from low spectral components can adapt that derived from higher components. Thus, the data indicate both generalized and specialized extraction of pitch.

It is not immediately clear why a pitch extraction mechanism that was specialized to note the origin of the stimulus might evolve. There are at least two possible benefits for having the pitch extraction mechanism sensitive to the type of peripheral information which comes to it, however. First, such sensitivity may aid in the localization of a sound (binaural sensitivity). Secondly, such sensitivity may aid in identifying the sound source by means of timbre (spectral sensitivity). It should be noted that the notion of a pitch extractor specialized for spectral content from each ear agrees well with data reported by Hall and Soderquist (1975). They found that the perception of residue pitch depended upon the way in which spectral components were distributed to each ear, indicating that pitch extraction was a specific rather than a general process.

One piece of data which deserves attention is the finding that a high spectrum did not adapt a 200 Hz residue pitch of low spectrum. Hall and Soderquist (1975) have reported that residue pitch derived from high-spectral components is much weaker or less perceptible than pitch derived from low-spectral components. It may be that low-spectral components activate all specialized pitch extractors somewhat, but a specialized low-component extractor maximally, as suggested earlier. High-spectral components, possibly because of their initial poor peripheral resolution, may not activate any pitch extractors any great amount (Wightman, 1973b, proposes something along this order). Although a high-spectral stimulus may activate more than its own specialized pitch extraction structure, such activation may be too weak to be detected in the experiments reported here. Incidentally, the fact that a high-spectral

200 Hz pitch adapted a high-spectral 200 Hz pitch more than a low-spectral 200 Hz pitch adapted a high-spectral 200 Hz pitch probably provides the best evidence for specialized pitch extraction structures. If there were simply a general 200 Hz extractor, the very strong 200 Hz pitch arising from the low spectral 200 Hz residue adaptation stimulus would be expected to greatly adapt the generalized extractor. When the relatively weak pitch of the high-spectral test stimulus was presented, a great degree of adaptation would be expected--greater than when the adaptation tone had been another relatively weak pitch of a high-spectral tone. However, a high-spectral tone clearly adapts a high-spectral tone more than a low-spectral tone adapts a high-spectral tone. Thus, the notion of a specialized pitch extractor is supported.

Sharpness of Adaptation Curves: Spectral Resolution

The finding that the adaptation curves in Figures 3-5 show relatively narrow tuning for the lower region and relatively broad tuning for the higher region agrees with previously reported pitch data. For instance, it is well known that the absolute frequency difference limen is greater for high frequencies than low; the critical band for frequency is larger for higher than for lower frequencies. In general, the higher frequencies are considered to be less well-resolved than lower frequencies. This is supported by the data: for the low region, the 3rd, 4th and 5th harmonics of 184 through 216 Hz adapt the 3rd, 4th and 5th harmonics of 200 Hz to some degree; for the higher region (9th, 10th and 11th harmonics), the region of adaptation is broadened to include the 9th, 10th and 11th harmonics of 168 through 232 Hz. What this means is that, for higher spectral regions, a greater number of residue pitches (and, therefore, a greater range of component frequencies) can result in activation of a pitch extractor. Thus, more pitch ambiguity would be expected with a high-frequency composition stimulus. In behavioral studies, more pitch ambiguity has been found for stimuli with higher spectral composition. A final indication of better resolution for the lower region is exemplified in Figures 3, 4, and 5. The results show a low region 200 Hz residue adapting a low region 200 Hz residue test stimulus, in contrast with a high region 200 Hz residue adapting a high region 200 Hz residue test stimulus. The low region adaptation is always greater than that in the higher region. This is probably due to less spectral "smearing" because of the better resolution in the low region.

The adaptation of high spectral components by low spectral components (Figures 6, 7 and 8) indicates some interesting properties of pitch resolution. The range of pitches from the low region which adapt the high region is relatively small, ranging from about 184 to 216 Hz. The data shown in Figures 3, 4 and 5 indicate that the 9th, 10th and 11th harmonics of 200 Hz show adaptation to 168 Hz through 232 Hz when the adaptation stimulus is from the high region; that is, the pitch extractor is sensitive to a wide range of pitches. When the adapting pitches are from the low spectral region, however, the same pitch extractor is sensitive to a much narrower range of pitches (from 184 to 216 Hz). It is apparent then, that the range of adaptation pitches is very much dependent upon how well the components of the adaptation stimulus are resolved. If the components making up a 176 Hz residue pitch are not well resolved, they will probably activate the high region pitch extractor. If, however, the components making up the 176 Hz pitch are well resolved (that is, from a low spectral region), the extractor is not activated.

One final item on spectral resolution concerns the binaural data. Not only did the binaural adaptation curves indicate less adaptation than monaural curves, but the curves were flatter as well. This would indicate less frequency resolution in the binaural pitch data. This decrease in resolution from monaural to binaural data would not be expected to be caused by peripheral factors. Instead, one might suppose that in transferring information from one ear to the specialized pitch extractor for the other ear, some frequency information becomes "blurred" or is lost.

Pitch Cues and Ambiguity

The experiment on cues for residue pitch or pitch ambiguity indicated that at least two consecutive harmonics of a fundamental are necessary in order to result in adaptation of a residue pitch. The adaptation of a 400 Hz residue pitch by a 200 Hz residue complex of 800-1000-1200 Hz has offered a quantitative measure of pitch ambiguity differing from that obtained from pitch-matching experiments. The data on pitch ambiguity may give a clue as to how frequency information is synthesized into residue pitch. They indicate that adaptation takes place only when two or more consecutive cues for a fundamental, or harmonics are presented. Non-consecutive harmonics are not sufficient as shown by the lack of 200 Hz adaptation with the 400-1400-2400 Hz adaptation stimulus. Thus, the pitch extraction mechanism must be activated only when the proper conditions of _number_ and _spacing_ of harmonics are met. The neural circuitry for this type of operation is not too difficult to imagine, however. In fact, cortical neurons in the cat which fire selectively to harmonically related stimuli have been reported (Katsuki, 1961).

The ambiguity data for the 800-1000-1200 Hz adaptation stimulus support subjective report: in subjective reports subjects usually report a pitch of 200 Hz when such a stimulus is presented, but 400 Hz is sometimes reported (Terhardt, 1974). The fact that the 200 Hz test stimulus suffered more adaptation than the 400 Hz test stimulus would agree with this finding (see Table 1). There were never two consecutive harmonics of 300 Hz in the adaptation stimuli, and no adaptation of the 300 Hz test stimulus was found. There is a possibility that one harmonic of a fundamental is sufficient to result in adaptation, but that such adaptation was so weak that it did not show up in the method used here. Such a possibility cannot be totally discounted.

Residue Pitch Versus Pure Tone Pitch

The finding that a 200 Hz pure tone did not result in adaptation of a residue pitch of 200 Hz definitely puts residue pitch in a different category from pure tone pitch. The fact that residue and pure tone pitch sound very different certainly causes one to doubt that their underlying neural processes are identical. The lack of adaptation in this experiment adds to this doubt. Unfortunately,what little we know about the anatomical correlates of pitch has resulted from experiments with pure tone pitch. Since most of daily human experience is with some form of residue pitch, the anatomical-pitch correlations reported may not be particularly relevant. For instance, it is reported that pitch discrimination is probably sub-cortical (Butler, Diamond, and Neff, 1957) since cats can make pitch discriminations without cortex. The perception of residue pitch involves the synthesis of frequency information and may, therefore, be regarded as a higher level process than simple frequency or pure tone analysis. The anatomical correlates of residue pitch perception can only be guessed at at this time.

AM Versus FM: Evidence Against Fine Structure Theories

The experiment on AM and QFM adaptation definitely indicates that the fine temporal differences in the stimuli are largely, if not completely, ignored. Each stimulus adapted the other equally. The differences between the two reported by Kay and Matthews (1972) is almost certainly a function of rate of modulation. Kay and Matthews used relatively slow rate AM and FM. Adaptation was strongly affected by whether AM or FM was used to adapt FM, so the auditory system seemed to be sensitive to AM-FM differences. In the present study, however, no adaptation differences were found. It is likely that in the fast-rate AM and FM used here, time cues were ignored and only spectral cues were critical. This result does not support the fine structure theories of pitch perception or the results of Ritsma and Engel (1964). Fine structure theories would predict unequal adaptation from AM adapting FM versus FM adapting AM.

CHAPTER V

SUMMARY

The data indicate the existence of specialized channels or pitch extractors for residue pitch. The specialization is for ear of signal presentation and spectral region of components. Because of binaural adaptation,residue pitch perception can be regarded as a central process, but the fact that pitch extraction seems to be specialized for each ear emphasizes the peripheral process of pitch perception as well. Adaptation curves reflect the existence of rather narrow pitch channels for low spectral region and wider channels for higher regions. The adaptation data show that pitch extraction appears to rely on spectral cues, ignoring subtle temporal or fine structure differences. Pure tone pitch and residue pitch extraction appear to be largely independent processes.

The data reported here are not thought to support any particular theory of residue pitch perception except to the extent that it does not favor fine structure theories. Goldstein's optimum processor model, Wightman's spectral autocorrelation model and Terhardt's pattern recognition model all contain principles which can be used to accommdate the data reported. Wightman's model already accommdates well the data on pitch ambiguity and pitch strength or perceptibility. The major theory reconstructions which are called for by the data here are considerations for the specialized nature of pitch extraction. both in terms of ear of presentation and spectral composition of the stimuli presented.

CHAPTER VI

FURTHER RESEARCH

Some directions for further research are suggested. Hall and Soderquist (1975), in a study of the strength of residue pitch, found that several factors made a residue pitch strong and unambiguous. One was that the components of a complex be from a low spectral region; another was that there be many rather than few components making up the complex; finally, there should be relatively large rather than small spectral spacing between the components. It has been shown here that when components are from a low spectral region, more adaptation occurs. A test could be made of whether the same holds true for larger component spacing versus smaller, and a greater number of components versus a fewer number. For instance, degree of adaptation of 200 Hz spacing versus 400 Hz spacing could be examined; adaptation could also be compared between a five-component complex versus a three-component complex. For larger component spacing, one might expect greater adaptation because of better resolution of components. For a greater number of components, one might expect more adaptation because more cues were adapting a pitch extractor.

In this study it was found that a high spectral region would not adapt a lower region. The spectral spacing between the two regions was great, however, spanning from the 3rd to the 11th harmonics. If the spacing between the two regions had not been as great, the higher region may have adapted the lower. This would be especially true if the higher region were around the 6th, 7th, and 8th harmonics, because these harmonics would be relatively well resolved.

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