Phonetic Experimental Research at the Institute of Linguistics University of Stockholm

PERILUS VI

Francisco Lacerda

Effects of peripheral auditory adaptation on the discrimination of speech sounds

December 1987
# ERRATA

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Some of the tables with statistical data were not included in the appendix. Those tables can be provided, if requested.
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PERILUS VI

Francisco Lacerda

Effects of peripheral auditory adaptation on the discrimination of speech sounds

December 1987
EFFECTS OF PERIPHERAL AUDITORY ADAPTATION
ON
THE DISCRIMINATION OF SPEECH SOUNDS

ABSTRACT

This study investigates perceptual effects of discharge rate adaptation in the auditory-nerve fibers.

Discrimination tests showed that brief synthetic stimuli with stationary formants and periodic source were better discriminated when they had an abrupt as opposed to a gradual onset (non-adapted vs adapted condition). This effect was not observed for corresponding stimuli with noise source.

Discrimination among synthetic /da/ stimuli (abrupt onsets) was worse than among /ad/ stimuli when the respective onset and offset frequencies of the second formant (F2) were varied. Similar results were obtained for /ba/ and /ab/. The low discrimination rate in consonant-vowel stimuli (CV) was explained in terms of sensory smearing of spectral information due to rapid formant transitions. Discrimination improved when the smearing effect was reduced by holding the onset formant pattern over a certain period of time of about 16ms. The relatively high discrimination score for the VC stimuli was explained by residual masking; extending the VC offset did not improve discrimination.

Discrimination of place of articulation in CV syllables was examined in the light of sensory smearing. Two continua of /bu-du/ and /ba-da/ utterances were used in discrimination and identification experiments. It was observed that the discrimination peak for /Cu/ was displaced from the /b/-/d/ boundary, towards a flat F2 transition, suggesting that optimal place discrimination is related to the stability of the auditory representations generated at onset. This result is discussed in relation to current views of categorical perception.

Key words: Adaptation, discrimination, categorical perception.
PERILUS VI

PERILUS mainly contains reports on current experimental work carried out in the Phonetics Laboratory at Stockholm University. Copies of PERILUS are available from the Institute of Linguistics, Stockholm University, S-106 91 Stockholm, Sweden.

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EFFECTS OF PERIPHERAL AUDITORY ADAPTATION ON THE DISCRIMINATION OF SPEECH SOUNDS
ACKNOWLEDGMENT

After an exciting, long and hard period of work, my text is finally ready!

Now, I would like to thank some of those who have directly been involved in this thesis of mine. I start by Professor Björn Lindblom from the Institute of Linguistics of the University of Stockholm. His encouragement, criticism and attitude towards research and life, have been an invaluable source of inspiration. Most of the ideas that I try to express in this thesis are, clearly, the result of the many discussions we had.

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Finally, I thank all my friends at the Institute of Linguistics of the University of Stockholm and at the Speech Transmission Laboratory of the Royal Institute of Technology: the former for caring and coping with my (often excessive) "progress reports" and the latter for their help with this final printing.

I am glad that all this writing is finished! (for the tenth time in the last two weeks!).

To
Amandina and Mariana
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STATEMENT OF THE PROBLEM

This work attempts to establish a link between some neurophysiological aspects of the auditory system and their consequences for the perception of speech. Most relevant studies have had two distinct orientations: while neurophysiological studies usually deal with auditory pathways of animals like cats or chinchillas (Bekesy, 1960; Kiang, Watanabe, Thomas and Clark, 1965; Flock, 1982; Palmer, Winter and Darwin, 1986; Carney and Geisler, 1986), the psychoacoustic studies usually describe human listeners' reactions to non-speech sounds (Houtgast, 1974; Stevens, 1975; Plomp, 1976; Zwicker and Feldtkeller, 1981; Horst, 1982; Tyler, 1988). The main goal of this work is therefore to relate these approaches by interpreting some neurophysiological data in terms of psychoacoustic phenomena relevant to speech perception. Specifically, this work will focus on the consequences that discharge rate adaptation in the auditory-nerve fibers may have in perception.

Most previous psychoacoustic research has not dealt with speech-like sounds, other than stationary vowels. Nevertheless, it has long been known that the response of the auditory-nerve fibers adapts under stationary stimulation (Kiang, N. et al., 1965). It has also been observed that discharge rate adaptation enhances the presence of new acoustic information in the speech signal (e.g. Delgutte, 1980). Yet, the role that peripheral auditory adaptation may play in the representation of speech sounds has only been studied in connection with long-term adaptation generated by vowels with static formant patterns (Summerfield, Haggard, Foster and Gray, 1984; Summerfield and Assmann, 1987). The purpose of this thesis is therefore to investigate the possible effects of rate adaptation on the auditory representation of non-stationary speech sounds.

Auditory-nerve fiber rate adaptation takes place shortly after the onset of a stationary stimulation and results in a drastic reduction of the dynamic response range of the peripheral auditory nerve fibers (Delgutte, 1980). At first sight, it might seem rather strange that the auditory system can afford such a degradation of the speech signal representation and yet display an excellent communicative performance.
However, in view of the fact that natural speech is not stationary and that the information content of stationary events is very limited, adaptation may turn out to be a powerful mechanism for enhancing important events in the speech signal. This notion is indeed supported by neurophysiological data obtained in animal studies (e.g. Delgutte, 1980, 1982). It is also the basic assumption underlying the series of perception experiments described in chapters 2 to 13.

Chapters 2 to 13 contain the original findings of this study. However, to give the necessary background to the non-specialized reader, I have also included, in chapter 1, a brief overview of some relevant psychoacoustic and neurophysiological aspects. The expert reader can simply skip chapter 1.

Finally, in chapter 14, I address possible implications of the experimental findings.

The results of the statistical analysis of the experimental data are shown in the appendix.
1. STRUCTURAL AND FUNCTIONAL ASPECTS OF THE AUDITORY SYSTEM

1.0 Purpose of this chapter

This work is not aimed to be a detailed study of the ear or the auditory system, as such. Rather, the objective is to study the role that the auditory system might have in constraining the choice of speech sounds that can be efficiently used in a given language. To achieve this goal one obviously needs to have some knowledge of the anatomical and physiological features of the auditory system. This chapter is intended to present the anatomical and physiological aspects of the (peripheral) auditory system that are relevant to the experiments and discussion in this work.

1.1. Basic anatomy and mechanics

The ear is the peripheral organ of the auditory system. It transforms acoustic signals into neural representations (1). As indicated in fig. 1, three different parts are usually distinguished: the outer, the middle and the inner ear.

The sound waves are received by the external portion of the outer ear and conducted through the ear canal until they reach the eardrum. The ear canal is a small tube, about 2.5 cm long. It behaves as an acoustic tube, closed at one end (that of the eardrum) and open at the other with a resonance frequency around 3400 Hz. As a direct consequence of this resonance, the outer ear enhances the frequencies at about 3400 Hz as they are transmitted to the eardrum.

The eardrum establishes the border line between the outer ear and the middle ear and is connected to the malleus, the first of the three auditory ossicles that constitute the middle ear. The sound pressure exerted upon the ear drum is transmitted by the auditory ossicles to the oval window. There are three important functions performed by the middle ear: pressure equalization, protection of the inner ear against high levels of stimulation and transmission of energy from the external gaseous medium to the liquid medium of the inner ear.

The inner ear is where the actual transformation of mechanical excitation into neuronal impulses takes place. Since the characteristics of the neuronal responses

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1. For a detailed description see, for instance, Denes and Pinson (1963), chp. 5.
generated by the inner ear play a central role in the experiments of the next chapters, it may be useful to provide a more detailed description of the inner ear.

The inner ear consists of an intricate system of canals encased in bone and cartilage, the so-called labyrinth (fig. 1). These canals are filled with liquid and they have, in some regions, specialized transducers, the hair cells (2), which transform mechanical action into electrical impulses. When the cilia are deflected by mechanical action, the hair cell becomes polarized and it transmits an electrical impulse to the afferent auditory-nerve which, in turn, transmits the impulse further, along the auditory system’s pathways, to the brain. Usually the functions of the inner ear are divided into balance control and hearing. Although this is a useful distinction, it is interesting to note that the balance and hearing functions are actually two different developments of the same principle (Hudspeth, 1983).

The common aspect relating balance and hearing is that motion of the liquid in the canals of the labyrinth causes the cilia of the hair cells to deflect with subsequent generation of electrical impulses that are transmitted to the brain. The main difference between balance and hearing is that while balance depends on inertial forces developed when the organ is submitted to accelerations, the activation of the hair cells assigned to hearing is mediated by the action of the stapes upon the oval window.

It is in the cochlea that the actual transformation from the acoustic medium into a neuronal coding takes place. The hair cells are the transducers between mechanical stimulation and electrical impulses.

The human cochlea is basically a 35mm long tube that is twisted into a spiral, like the shell of a snail (fig. 2). There are three different regions (more easily observed in the unrolled cochlea of fig. 3). Along the cochlea runs the cochlear partition. This partition starts at the cochlea’s basal end, between the oval and the round windows, and terminates near the apical end. It divides the cochlea into two parts: the scala vestibuli, in contact with the oval window, and the scala tympani, on the side of the round window. The two scalae communicate with each other at the cochlea’s apical end, via an opening named helicotrema. The scalae (and for that matter the semicircular canals too) are filled with a liquid called perilymph. The cochlear

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2. These transducers are called the hair cells because they have a number of small cilia that look like hairs.
partition is divided from the scala vestibuli by the Reissner’s membrane and from the scala tympani by the basilar membrane (fig. 4). This partition is filled with a liquid, the endolymph, which fills the volume between the Reissner’s membrane and the basilar membrane, known as the cochlear duct. In this duct is the organ of Corti, which essentially consists of a group of hair cells and a membrane, the tectorial membrane.

![Fig.2 Cochlear portion of the inner ear.](image)

The action of the stapes upon the oval window causes the perilymph of the scala vestibuli to be displaced. Because liquids are practically incompressible and the walls of the inner ear are rigid, the displacements of the perilymph in the scala vestibuli are communicated to the perilymph in the scala tympani and ultimately compensated by displacements of the round window.

If a sound is heard, the pressure variations from the gaseous medium are communicated to the stapes which vibrates, acting as a piston on the oval window. In consequence pressure waves are created in the perilymph. Since it takes time for a pressure wave to travel from the oval to the round window (i.e. from the basal end up to the apical end, along the scala vestibuli, and then back again, through the helicotrema and along the scala tympani, to the basal end, (fig. 4), the forces acting on each side of the cochlear partition are not equal all the time during the propagation. This results in displacements of the cochlear partition at those points where the force exerted by the pressure wave traveling through the scala vestibuli is not canceled by the force associated with the pressure wave in the scala tympani.

The mechanical properties of the cochlear partition change along its length. The basilar membrane is very thin at the basal end and thicker at the apical end. The change in the mechanical properties of the cochlear partition along its length explains most of its deformation patterns as response to acoustic stimuli (3).

The pattern of vibration of the cochlear partition has its maximum amplitude at a point along the partition that is related to the frequency of excitation. For low frequency sine-wave excitation, the maximum occurs near the apical end (i.e., near the helicotrema). As the excitation frequency increases the location of the maximum of vibration of the cochlear partition is displaced towards the basal end.

3. It is possible to predict the details of the building up of forces that act upon the cochlear partition deforming it, but cochlear mechanics will not be discussed here (see, for instance, Rhode, 1978; de Boer, 1979).
When the basilar membrane is set into vibration the hair cells of the organ of Corti, which are implanted among support cells that are connected to the basilar membrane, are stimulated. In the organ of Corti there are three rows of outer hair cells and one row of inner hair cells (4). The vibration of the basilar membrane creates mechanical excitation of the hairs of the hair cells, by contact with the tectorial membrane (5).

Fig. 3 Unrolled cochlea showing its partitions.

Fig. 4 Cross section of the cochlea.

4. The designation of outer and inner hair cells comes from their position on the cochlea, relative to the inner side of the spiral, consisting of a bony shelf through which the auditory-nerve fibers connected to the hair cells run. There are about 20,000 outer hair cells and 3,500 inner hair cells.

5. The similarity between the generation of the neuronal coding in the cochlea and that of the balance organs is striking. It suggests that the spiral arrangement of the cochlea, along with the fixation of one of the ends of the tectorial membrane, are design features to minimize auditory disturbances that would otherwise be caused by accelerations of the organ.
1.2. Basic neurophysiology of the auditory system

The electrical impulses generated by the hair cells have to be further transmitted to the brain. This is accomplished by the neurons of the auditory system. The neurons are specialized cells that, when appropriately excited, generate and transmit electrical impulses. There are different types of neurons but they all have a common structure. The neurons (fig. 5) have a cell body inside of which is the nucleus. Extending from the cell body there is a long filament, the axon, that is able to carry electrical impulses over large distances. The axon terminates in a series of ramifications forming the terminal arbor (fig. 5). Around the cell body are a number of finger-like extensions, the dendrites.

![Fig. 5](image-url) Representation of a neuron and synaptic connections.

A neuron receives stimulation from another neuron at junctions called synapses. A synaptic junction is often a contact between the terminal arbor of a neuron and the dendrites of another but the nerve endings of a neuron can make direct contact with the cell body of another, bypassing the dendrites.

The basic functioning principle of a neuron is, at first sight, relatively simple. When it receives a strong enough electrical impulse from a preceding neuron, it generates another impulse that travels along the axon and through the terminal arbor until it is transmitted to the next neuron. In this respect, a neuron works simply like a relay station retransmitting the information received.

The electrical response of a neuron is, however, complicated by, at least, three additional facts (Rose, 1976, chap. 3): first, the stimulation level must be above a certain threshold in order to cause the neuron to fire; second, just after firing, the neuron cannot fire again, within one to two ms, regardless of the intensity of the stimulation (absolute refractory period) and within about 10 ms it will have a higher
firing threshold (relative refractory period); third, the impulses received from previous neurons may be inhibitory, i.e. they raise the excitation threshold of the neuron.

These three aspects have important consequences in that the neuron turns out to be much more than a simple relay station for electrical impulses. Rather it is a complex processor whose response is not linearly related to the amount of stimulation received. Since some of the synapses are excitatory (i.e. they facilitate firing of the neuron) and others are inhibitory, the response of the neuron depends on the combination of excitatory and inhibitory stimuli and on the amount of time that the neuron has been at rest.

In the auditory pathways there are tens of thousands of interacting neurons involved in the connection between the inner ear and the auditory cortex. It is not difficult to realize that the overall performance of such a transmission system can become extremely complex.

The hair cells of the organ of Corti (fig. 6) stimulate the peripheral endings of the afferent auditory-nerve fibers. The bodies of the auditory-nerve fibers serving a certain region of the cochlea are grouped in the spiral ganglia. The axons of the auditory-nerve fibers extend from the ganglia to the central nervous system (fig. 7).

The central processes of the auditory nerve cells form the auditory nerve connecting the spiral ganglia to the cochlear nucleus. The number of fibers in the auditory-nerve varies from species to species. In the human auditory-nerve there are 25 to 30 thousand fibers in this nerve.

At the cochlear nucleus the first synaptic connections are found. The signals received from the hair cells by the ganglion cells are transmitted to a second set of neurons. These neurons receive connections from a number of fibers coming from the spiral ganglia. Once more, the synaptic connections are not one-to-one, as to enable tracing the signals received from a single spiral ganglion nerve fiber in all their way up to the auditory cortex. Rather, as was pointed out before, each of the neurons originating at the cochlear nucleus receives both excitatory and inhibitory synaptic connections from many spiral ganglion cells - which, in turn may receive excitation from more than one hair cell.
From the cochlear nucleus the signals are transmitted to the next synaptic connection at the superior olivary complex. After passing through a new intricate system of synapses, the signals are transmitted to the last synaptic station before the auditory cortex, the medial geniculate body. The neurons originating at the geniculate body terminate directly in the auditory cortex.

There seems to be evidence that a considerable amount of information processing takes place at the synaptic connections but the exact details of this processing are not yet well understood.

For the remainder of this study, the term "auditory-nerve fiber" (ANF) will refer to the afferent spiral ganglia nerve cells of the peripheral auditory system. Unless otherwise stated, then, the level of the cochlear nucleus will not be further considered.

The nerve-cells of the spiral ganglia receive their excitation from the hair cells. The electrical impulses travelling along an auditory-nerve fiber therefore reflect the stimulation generated by the group of neighboring hair cells to which the fiber's dendrites are connected. Since stimulating the ear with a pure tone produces a spatially concentrated excitation of the basilar membrane, a limited set of auditory-nerve fibers will respond to a given tone. However, the relation between the mechanical excitation of the basilar membrane and its neural consequences is not straightforward. The hair cells of the organ of Corti are not connected one-to-one to the auditory-nerve fibers. Although there are many fewer inner hair cells than outer hair cells, 95% of the afferent neurons are connected to inner hair cells and only the remaining 5% establish synapses with outer hair cells (Spoendlin, 1974). The situation is further complicated by the fact that each inner hair cell is connected to about 20 different afferent auditory-nerve fibers, while about 10 neighboring outer hair cells - responding to slightly different frequencies - are connected to the same afferent auditory-nerve fiber (Spoendlin, 1974). Since the majority of the auditory-nerve fibers are connected to an inner hair cell, most of the neurophysiological data refer to responses of inner hair cells. This may allow valid relationships between the psychoacoustic and physiological effects of pure tones to be established. However, the complexity of this relation increases enormously as complex stimuli are used to generate spatially distributed excitation along the basilar membrane.

The electrical signals traveling along the auditory-nerve fibers can be monitored by introducing micro-electrodes into the auditory-nerve. These electrodes are usually placed in the axons of the spiral ganglia cells and not nearer the hair cells in order to minimize the risk of mechanical damage. Measurements have been made directly on the hair cells in order to study their mechanical properties (Flock, 1982).

The insertion of a micro-electrode cannot be directed to a predefined auditory-nerve fiber. The frequency range to which the fiber responds is determined by stimulating the ear with a tone whose frequency is continuously increased or decreased. By means of such a sweep tone, the fiber's response to each frequency can be observed. The frequency of the tone to which the fiber responds maximally is the so-called characteristic frequency of the fiber. Different fibers have different characteristic frequencies, reflecting the region of the basilar membrane from which they receive excitation (6).

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6. Note that the neuron has no intrinsic resonance frequency. The response maximum at a certain frequency is a consequence of the tonotopical organization of the inner-ear. A pure tone generates mechanical excitation in a certain region on the basilar membrane and consequently the nerve fibers connected to the hair cells of that region will fire in response to the received stimulation.
1.3. Frequency coding in the auditory nerve fiber

1.3.1. Response to stationary acoustic stimulation

A living neuron always displays a certain level of spontaneous electrical activity. The auditory-nerve fibers can be classified in terms of their spontaneous activity (M. Liberman, 1978): low/medium spontaneous rate (including fibers with a discharge rate up to 20 spikes/sec) and high spontaneous discharge rate (from 20 up to 100 spikes/sec). According to M. Liberman's (1978) estimate, about 40% of the auditory-nerve fibers have low/medium spontaneous rates. Obviously then, saying that a fiber starts firing means that its firing rate has increased above the normal spontaneous firing rate.

Although an auditory-nerve fiber fires optimally when stimulated at its characteristic frequency, it can also respond to stimulation at other frequencies, provided that the stimulation level is increased. The sensitivity of auditory-nerve fibers to different frequencies is usually presented in frequency tuning curves (also referred to as frequency threshold curves). Examples of such curves are shown in fig. 8 (single auditory-nerve fibers of the cat).

Each frequency tuning curve is obtained by placing an electrode in one auditory-nerve fiber and stimulating the ear with tones of different frequencies. For each frequency, the frequency tuning curves indicate the lowest intensity level for which an increase in the spontaneous firing rate of the fiber is observed.

The shape of the frequency tuning curves for the cat shown in fig. 8, varies a little with the characteristic frequency of the fibers: fibers with characteristic frequencies below about 1kHz have broad and roughly symmetrical tuning curves; fibers with characteristic frequencies in the range from about 1kHz to about 5kHz are typically asymmetrical. These frequency tuning curves have a tail that extends to the frequencies below the characteristic frequency of the fiber and an abrupt flank for frequencies above the characteristic frequency. The sensitivity decreases rapidly for frequencies above the fiber's characteristic frequency, but slowly for stimulation below the characteristic frequency. A consequence of this asymmetry is that a tone of moderate intensity will excite more fibers with characteristic frequencies above the tone’s frequency than fibers with characteristic frequencies below that of the tone (7). The firing rates of the population of auditory-nerve fibers responding to a pure tone will have a pattern like that of fig. 9.

7. The response of the "off-tune" fibers decreases with the distance between the fibers’ characteristic frequency and the frequency of the excitation tone but it decreases more rapidly for fibers with characteristic frequencies below than for those with characteristic frequencies above the stimulating frequency.
Fig. 8 Frequency threshold curves for single auditory-nerve fibers of the cat (From Kiang et al., 1965. Reprinted with permission of the authors).
Fig. 9 Estimated excitation pattern produced by a sinus tone.
Tones of different frequencies produce mechanical excitation at different places along the cochlea. The discharge pattern of the population of auditory-nerve fibers thus contains information about the frequency components present in a complex acoustic stimulus. The frequency of the components are converted into spatial location and represented by the fiber's characteristic frequencies. The intensity of each component is coded by the rate of discharge: when the intensity of the frequency component is just above the frequency tuning curve of a given fiber, the fiber responds with a small increase in its spontaneous firing rate. As the intensity of the component increases, the firing rate of the fiber also increases. To put it simply, the auditory system can be thought of as coding frequency information by keeping track of the fibers that are excited by the acoustic stimulus (associated with regions of excitation on the basilar membrane) and coding intensity information as increases in the firing rate of the stimulated fibers. In this sense, the pattern of discharge represents a spectral analysis (8) of the acoustic input in the form of an amplitude spectrum.

![Figure 10](image)

Fig. 10 Auditory-nerve fiber’s discharge rate versus intensity of stimulation at different moments along a stationary stimulus (From Delgutte, 1980, with permission of the author and publisher).

However the firing rate of an auditory-nerve fiber cannot increase indefinitely. As shown in fig. 10, the function relating firing rate to intensity of stimulation is not linear. Rather, it reaches a plateau for a certain intensity level and all the intensities above that are coded as the same firing rate. The discharge rate of the auditory-nerve fiber saturates, i.e. it cannot increase further, even if the intensity of the stimulation increases. The range of intensities for which an auditory-nerve fiber can respond with proportional increases of its firing rate is called its dynamic range. Surprisingly though, the dynamic range of a nerve fiber’s average discharge rate is quite limited compared to the range of intensities of the sounds in a normal acoustic environment. They typically extend over only 20 to 30dB. It is intriguing that auditory-nerve fibers with such small individual dynamic ranges are able to code sounds that usually have much wider dynamic ranges. However since different fibers, with different spontaneous rates, have different lower and upper limits for their linear responses, it has been suggested (Young and Sachs, 1981; Greenberg, 1986; Delgutte, 1987) that fibers with different spontaneous rates and about the same characteristic frequencies

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8. Spectral analysis (obtaining the amplitude spectrum) of a sound consists in finding which are the frequencies and the intensities of the pure tones that, summed, will synthesize it.
may work together. Thus, when some of them have attained saturation of their mean discharge rates, others, responding within their dynamic range, take over. This could be achieved by combining the responses of the fibers with high spontaneous activity (i.e., start responding at lower intensity levels but saturate after about 30dB) with those from low spontaneous activity fibers which have higher thresholds of stimulation but also wider dynamic ranges. Even so it is not clear how this could be accomplished. Since the low spontaneous activity fibers represent less than 10% of the entire population of fibers.

Another way in which the ANFs can code the frequency components present in the acoustic stimulus is in terms of the time structure of their discharge patterns (Galambos and Davis, 1943). The discharges of an ANF tend to be synchronized with the amplitude variations of the frequency component the fiber is responding to. This is often referred to as "phase locking". The ganglion cell tends to generate impulses during a certain phase of the amplitude oscillations of a given frequency component. An interesting aspect of the phase locking phenomenon is that in spite of discharge rate adaptation, the ANFs may still provide information about stimulus frequencies by means of their synchronized responses (Johnson, 1980). Recent findings (Greenberg, Geisler and Deng, 1986) show that frequency selectivity was preserved in ANF timing patterns. If spectral representation is to rely only on the discharge rate of the ANFs, then, since the average discharge rate does not convey frequency-specific information, "the spectral pattern of the acoustic signal must be derived on the basis of the topographic distribution of discharge rate information across a population of cochlear fibers. If most fibers are discharging at saturation level, then it will be difficult to infer the location of spectral prominences on the basis of spatial pattern of rate activity" (Greenberg et al., 1986, p.1017). Since "saturation does not affect the frequency-encoding capabilities of timing information (...) because the timing of discharge activity conveys frequency-specific information which is preserved even at suprasaturation intensities" (Greenberg et al., 1986, p.1017), neural synchronization can explain the preservation of spectral information, even for saturated average discharge rates. Nevertheless, there are limitations in this synchronization account: one of them is that synchronized responses do not convey amplitude information about the acoustic stimuli; another limitation is that the synchronized response disappears for frequencies above 4 or 5kHz (Evans, 1982). This means that, above this frequency limit, the representation of sound stimuli must rely exclusively on the discharge rate profile of the ANFs (J. Rose, Brugge, Anderson and Hind, 1967). In favor of the synchrony approach, it may be argued that the lack of amplitude information is a minor problem. It has, in fact, been observed that spectral tilt variations have only moderate consequences in the perception of vowel quality (Carlson, Granström and Klatt, 1979). The possibility of ignoring amplitude information is further supported by the good estimates of vowel dissimilarity that could be obtained with an auditory model like DOMIN. This model, developed by Carlson and Granström (1979, 1982), does not make use of amplitude information and yet it produces good estimates of vowel dissimilarity.

At any rate, although amplitude information may not be crucial for the identification of vowels, it definitely plays a role when the vowel sounds are on the boundary between two vowel categories (Chistovich, 1971). It is therefore likely that the speech perception mechanism takes advantage of both the time structure and the discharge rate of the ANFs’ responses. By combining non-adapted discharge rates at the onset of stimulation (fig. 10) along with phase-locking after adaptation has taken place, it may be possible to explain how the auditory system succeeds in generating adequate auditory representations of the acoustic stimuli.
1.3.2. Response to dynamic acoustic stimulation

The discharge rate patterns discussed so far have referred to stationary (9) acoustic stimuli with long durations. However, these characteristics are shared by most sounds. Typically, sounds used for communication, and speech sounds in particular, are poorly represented by long stationary stimuli. Vowels, liquids and nasals can be roughly considered as stationary. However, their stationary intervals do not usually last for more than about 100ms to 200ms, in the case of hyperarticulated speech. In colloquial speech the durations are much smaller and stationariness often disappears as coarticulation effects become stronger (Lindgren, Krull and Engstrand, 1987). In contrast, durations of stationary laboratory stimuli typically fall in a 500ms to 1s range. This discrepancy between long stationary laboratory stimuli and the normal type of acoustic stimulation of the auditory system, called for a closer investigation of the auditory system's response to more meaningful acoustic stimuli.

The problem has been treated by several authors (Kiang et al., 1965; Smith, 1979; Delgutte, 1980; Smith and Brachman, 1980). It was shown that the discharge rate is not constant during the response to a long, stationary stimulus. In the work of Smith (1979), for instance, extensive measurements of the firing rates of single ANFs showed that the steady state response of the nerve fiber has a much smaller dynamic range than the nerve fiber's response at the onset of stimulation. This is a consequence of adaptation of the ANFs: at the onset of stimulation, the fiber responds with a high firing rate but the rate decreases shortly after, even though a constant stimulation level is maintained.

The consequences of adaptation of the ANFs are very important for the representation of sound by the peripheral auditory system. Since an ANF, initially at rest, has a much larger dynamic range just after the onset of stimulation than 10-20ms later (see fig. 10), the spectral characteristics of the stimulus at the onset, may be more salient than those that are processed after adaptation of the ANFs has had time to occur.

In the light of the adaptation phenomenon the "place theory" (10) gains more explanatory power. The profile of the discharge rate of a population of ANFs just after the onset of stimulation may provide a good description of the spectral characteristics of the acoustic stimulus because the dynamic range of the fibers is wider at onset. Assuming that the psychoacoustic auditory representation of the stimulus is given by the representation that a stimulus can elicit in the peripheral auditory system, one may...

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9. In this context, "stationary", refers to stimuli whose spectral characteristics do not change with time (e.g. a sustained vowel, a pure tone).

10. This theory explains the auditory representation of sound as the result of the profile of the discharge rate pattern of the NFs. Since in the cochlea different frequencies produce excitation at different places along the basilar membrane, the place from which the ANFs receive their excitation gives information about the frequency components of the signal while the discharge rate is associated with the component's intensity.
expect the initial part of the stimulus to be most favorable for the extraction of spectral information.

The possible psychoacoustic consequences of the neurophysiological adaptation phenomenon were studied by Chistovich (1971). Her experiment consisted in presenting a four formant synthetic vowel in which the second formant had a delayed onset relative to the synchronous onset of F1, F3 and F4 (fig. 11, top). The subjects were asked to adjust the level of the F2 in order to perceive a given vowel (fig. 11, center). It turned out that, to keep constant the vowel quality, the subjects decreased the level of F2 as the onset of F2 was increasingly delayed (fig. 11, bottom). In terms of the place theory, this result can be interpreted as indicating that adaptation has consequences for the auditory representation. The onset of stationary stimulation in the channels associated with F1, F3 and F4 causes adaptation of the ANFs responding to the frequencies of these formants, but it does not affect the F2 frequency channels. When the F2 stimulation is switched on, the corresponding fibers have not been adapted. Consequently, they will respond with a wider dynamic range than the fibers already being engaged in response to the other formants. The profile of the discharge rate across the population of ANFs displays therefore a prominent peak at the F2 frequency.

Fig. 11 Evolution of F2 level as a function of onset delay. (Redrawn from Chistovich, 1971).

Another important aspect of the dynamic response of ANFs is related to their refractory period. After the offset of stimulation, a fiber does not immediately recover from the adaptation. The persistence of the adaptation depends on the duration and intensity of the previous stimulation (Harris and Dallos, 1979).

The latter phenomenon seems to be involved in the generation of the so-called "auditory afterimages", similar to those occurring in vision. For example, after having listened to a notched white noise masker, Zwicker (1964) noticed that he could hear a tone at the frequency of the notch filter when the masker was switched off. The phenomenon, that he called a "negative afterimage" in hearing, could be explained as a direct consequence of the adaptation of the ANFs. The channels that had been exposed to the noise masker had adapted to the excitation level and therefore their firing rate had decreased to the adapted firing rate. When the notched masker was interrupted and a white noise masker switched on, then the unexposed channels could respond with non-adapted firing rates. Those rates were therefore higher than the discharge rates coming from the neighboring, adapted channels. As a consequence, an auditory pattern
with a prominent peak at the notch filter's frequency was built up and a tone corresponding to that auditory pattern was heard.

A more recent paper by Summerfield et al. (1984) demonstrates the possibility of perceiving vowels from uniform spectra as a direct consequence of the adaptation of the ANFs. They used a masker in which the formants of a vowel were represented by valleys instead of peaks. By exposing a listener to this masker, the ANFs normally responding to the valleys of the vowel spectrum are adapted, while those that would respond to the formant peaks are not. As a consequence, when a sound with an uniform spectrum is presented immediately after, the auditory system generates a vowel percept because the non-adapted fibers at the formant frequencies respond more vigorously than the others.

For this thesis adaptation is interesting from, at least, two points of view:

One has to do with the relationship between responses of single ANFs and the auditory representations of the speech stimuli, namely the existence of a psychoacoustic counterpart of the adaptation phenomenon of ANFs. This is an important question because in spite of what might be known and understood from a purely neurophysiological point of view, adaptation is only relevant here to the extent that it can be linked with the perception of speech sounds. In general terms, Zwicker's (1964) finding and the experiments of Chistovich (1971) and Summerfield and Assmann (1986) clearly support the notion that ANF adaptation has direct consequences for psychoacoustic phenomena.

The other point of view is not explicitly developed here. It is a general perspective of the communication problem within which there are possible ecological benefits of ANF adaptation. However, this perspective is only some sort of basic attitude throughout the thesis. Discussing it on the basis of the experiments below would be interesting but mainly speculative.

1.4. Basic psychoacoustic phenomena

The previous section dealt with responses of particular ANFs. The present section, in contrast, will focus attention on properties of the global response of the human auditory-system. From a perceptual point of view, neural responses of the auditory system are obviously of interest only to the extent that they can be identified by the human listener. There are several general psychoacoustic mechanisms acting to constrain our capacity of identifying and discriminating speech sounds. For the purposes of this study, the next sections will briefly address some key concepts like the critical bandwidth, masking and contrast enhancement by lateral suppression. For a comprehensive introduction to psychoacoustics see (Zwicker and Feldtkeller, 1981).
1.4.1. Critical bands and loudness summation

When two tones far apart in the frequency scale are presented to an observer, their perceived loudness is roughly the sum of the loudness of each one of the tones, presented in isolation. However, if the frequency spacing between these two tones is small, the resultant loudness is no longer the sum of their individual loudnesses. Instead of a loudness summation, the two tones produce a resultant loudness that is that of a signal having the sum of the power of the component tones (Fletcher, 1953). Specifically, if two tones of equal intensity and of very near frequencies are presented together, the loudness of the complex corresponds only to that of a tone that is 3dB more intense than the component tones (3dB increase in the intensity is the result of a simple doubling of the energy). Loudness summation does not occur until the frequency difference between the two tones exceeds a certain critical value which is called "critical bandwidth" or critical band (Zwicker, Flottorp and S. Stevens, 1957) and plays a central role in psychoacoustics.

The critical bandwidths are frequency dependent. Dividing the frequency scale into critical bands (Zwicker, 1960) gives the "critical-band rate" scale or Bark scale, shown in fig. 12. There is an approximate proportionality between the Bark scale and the mel scale of perceived pitch. Furthermore, one Bark corresponds to an approximately constant distance along the basilar membrane (1.3mm, according to Zwicker and Feldtkeller, 1981). The critical band rate of a tone is proportional to the location of the excitation maximum on the basilar membrane. The Bark scale is for this reason often called a tonotopical scale (11). There seems to be a clear relationship

Fig. 12 Bark and frequency relation. (From Traunmuller, 1983, with permission of the author.)

11. Tono + topical, relating frequency to place.
between psychoacoustics and the anatomy and neurophysiology of the peripheral auditory system.

The importance of the frequency to critical band transformations has stimulated the search for mathematical expressions to transform Hz into Bark (and Bark into Hz) as alternatives to the use of tables. These expressions do not capture the nature of the tonotopical scale, in the sense that, for instance, S. Stevens power law (S. Stevens, 1965, 1975) tries to reflect an intrinsic relationship between excitation and sensation. These formulas are simply the result of curve fitting procedures and are important since a mathematical description can be used in the conversions. There have been several suggestions for the Hz into Bark transformation. The expressions proposed by Schroeder, Atal and Hall (1979) were

\[
f = 650 \cdot \sinh \left( \frac{z}{7} \right),
\]

\[
z = 7 \cdot \ln \left( \frac{f}{650} + \left( \frac{f}{650} \right)^2 + 1 \right)^{1/2},
\]

where \( f \) is the frequency in Hz and \( z \) the value in Bark corresponding to that frequency. Matching to the experimental Bark scale is accurate for frequencies up to about 4kHz. Another expression was proposed by Zwicker and Terhardt (1980), this one also involving transcendental mathematical functions. A more simple mathematical expression was, however, presented by Traunmuller (1983):

\[
z = 26.81 \cdot \frac{f}{(1960+f)-0.53}
\]

\[
f = 1960 \cdot \frac{(z+0.53)}{(26.28-z)}
\]

These expressions will be used in the course of this work because they involve only elementary mathematical operations and approximate well to the tabulated standard average critical band values published by Zwicker (1960).

1.4.2. Masking

When a loud and a weak sound are presented simultaneously, the louder sound can dominate the percept in such a way that the weaker is simply not heard. The masking phenomenon can be explained in neurophysiological terms. A sound reaching the auditory system produces excitation of a number of ANFs related to the frequency components present in the sound. The firing rate of each ANF codes the intensity of the spectral components of the sound at the fiber's characteristic frequency. If a weak sound is present at the same time in a frequency channel that is strongly excited by a loud sound, there is no way in which the ANF can signal the presence of the weaker sound. The weaker sound, alone, would elicit a lower firing rate than that already present in the channel. The excitation level in that channel cannot be lowered to the level corresponding to the weaker stimulation. This effect is often called the "busy line phenomenon" because of its resemblance to the situation where a telephone line assigned to a certain telephone call will not transmit others.
This neurophysiological account facilitates inferences about psychoacoustic aspects of the masking phenomenon. The psychoacoustic masking pattern produced by a pure tone can be predicted from the shape of the physiological tuning curves of ANFs (fig. 8). A 1kHz tone at -80dB in the intensity scale of the figure, will excite mostly the fibers with characteristic frequencies around 1kHz, but fibers at higher and lower frequencies will also respond to the stimulation. Because the tails of the tuning curves extend mainly towards frequencies below their characteristic frequencies, many fibers with characteristic frequency above 1kHz will respond to the stimulation. These fibers will then signal the presence of energy in the channels of their characteristic frequencies. A similar result is observed for frequencies below that of the stimulating tone. The number of fibers responding to the 1kHz tone is, however, much smaller because the slopes of the tuning curves are much steeper for frequencies above their characteristic frequencies than for frequencies below. Assuming that the magnitude of the response given by each ANF is proportional to the difference between the excitation level and the fiber's threshold, the excitation pattern produced by a single tone turns out to be like the one shown in fig. 9. A tone at 1kHz produces more excitation in frequency channels above 1kHz than in channels below 1kHz.

The "busy line" model of masking has practical applications in non-invasive psychoacoustic methods for measuring excitation patterns produced by acoustic stimuli. To measure the excitation pattern generated by a sound, that sound can be considered as a masker. Using a sinusoidal test tone to determine the masking level produced by that sound at each frequency, a measure of the excitation elicited by the masker sound can be obtained. In practice this is done by presenting the test tone at different frequencies and having a subject adjust the test tone's intensity until the presence of the test tone can just be detected (12). This is the basic principle of the so-called simultaneous masking technique (13) of psychoacoustic assessment of excitation patterns produced by acoustic stimuli.

There are also non-simultaneous masking techniques in which the test tone is presented before (backward masking) or after the masker (forward masking). The masking levels depend on the time interval between the test tone and the masker. The so-called pulsation threshold technique is another variant of non-simultaneous masking. The technique explores the continuity effect (Thurlow and Elfner, 1959; Elfner, 1971) and the test tone and the masker are presented alternatingly (Houtgast, 1974).

1.4.3. Lateral suppression

A puzzling aspect of the excitation patterns obtained using simultaneous masking techniques is that the auditory patterns of stationary vowel-like sounds provided quite a pale picture of the original spectral detail. This was particularly evident for the case

12. The sinusoidal test tone functions as a probe and is often referred to by the term "signal".
13. "Simultaneous masking" simply means that the test tone and the masker are presented simultaneously.
of back high vowels for which the two neighboring formant peaks appeared simply as a single broad peak (Tyler and Lindblom, 1982)

Along with these psychoacoustic observations there were neurophysiological results suggesting the possibility of a contrast enhancement mechanism able to resolve neighboring formant peaks. In fact, similarly to what has been observed in studies of vision, neurophysiological studies of the activity of the ANFs have revealed non-linear contrast enhancing mechanisms, termed "two-tone inhibition, two-tone" (Nomoto, Suga and Katsuki, 1964; Sachs and Kiang, 1968). The phenomenon consists of a reduction in the firing rate of an ANF responding to a tone, when a more intense tone is simultaneously presented at another frequency (14).

Rainbolt and Small (1972) attempted a psychoacoustic demonstration of this effect, but the first clear results were obtained by Houtgast (1974). The key to the problem was the use of a non-simultaneous masking technique in the measurements. The term "lateral suppression" was then suggested by Houtgast for the psychophysical phenomenon (Houtgast, 1974, chap. 2).

The reason why it was not possible to observe the phenomenon using simultaneous masking techniques is that the stronger tone, the so-called suppressor, suppresses equally the masker (15) and the signal, under simultaneous masking conditions. The observation of lateral suppression depends on the use of non-simultaneous masking, non-simultaneous techniques. Lateral suppression was extensively studied by Duifhuis (1980), concerning the relationships between the amount of suppression and the frequency and intensity differences between suppressor and masker.

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14. The frequency and intensity of the inhibitory tone must have a certain relation to the frequency and intensity of the first tone. The point here is just to mention the existence of the inhibition phenomenon. Check the references for details.

15. Also termed "suppressee".
THE ROLE OF STIMULUS ONSET CHARACTERISTICS

A consequence of the tonotopical organization of the inner ear is that the auditory representations generated by the discharge rates of the population of ANFs, can be viewed as the output of a filter bank that makes a spectral analysis of the incoming acoustic stimuli. However, because even for moderate excitation levels the discharge rate of the ANFs saturates shortly after the onset of steady stimulation, those auditory patterns are likely to be flattened as adaptation takes place (Chistovich, Lublinskaya, Malinnikova, Ogorodnikova, Stoljarova and Zhukov, 1982, p.166). To the extent that auditory representations are mediated by the profile of the nerve fibers' discharge rate, the representations generated by non-adapted fibers must be optimal for the extraction of detailed spectral information. In particular, this means that the discharge-rate responses' profile generated at the onset of acoustic stimulation provides a maximally "sharp" auditory representation.

2.0. DISCRIMINATION OF COMPLEX SPEECH-LIKE SOUNDS

The information content of an auditory representation cannot, today, be assessed by the direct application of masking techniques or inferred from recordings made in the ANFs. Even though spectral details may be well represented in masking patterns or in the profiles of the discharge-rates of ANFs, it remains an open question to what extent that information can be valuable to the listener. A possible solution is to study the quality of the auditory representations of the acoustic stimuli using discrimination experiments. To be able to discriminate between stimuli that are physically similar to each other, the listener must make maximal use of the auditory representations that those stimuli generate.

The goal of these experiments is to study the auditory system's capacity for discriminating among speech sounds. Although reference will be made to peripheral auditory representations, they are not of primary interest.

The speech-like characteristics of the stimuli used in the experiments derive mainly from the fact that their spectra have a formant structure similar to that of voiced speech sounds. Additionally, in most of the experiments, the formant frequencies are not stationary: they vary with time, mimicking the natural speech formant transitions that are observed after the release of stop-consonants. Most of these complex stimuli sound like short (about 50ms) CV utterances.
2. BRIEF, CONSTANT F-PATTERN STIMULI

2.1. Introduction

As discussed in a preceding section, there are psychoacoustic phenomena that can be interpreted as consequences of the adaptation of the discharge rate of the ANFs. That was the case for the above mentioned "auditory afterimages" observed by Zwicker (1964) and further studied by Wilson (1970), and of Chistovich's (1971) experiment with delayed onset of F2.

Chistovich's (1971) experiment showed dependence of the F2 level on the delay of its onset relative to that of the F1, F3 and F4 formants (fig. 11): to keep constant the vowel quality, the level of the delayed F2 formant had to be decreased to match the discharge rate in the channels already responding to the other formants at the moment of the F2 onset. This result is inconsistent with the observed relative independence of the vowel quality on spectral tilt (Klatt, 1979; Carlson and Granström, 1979). It is however possible that the relative intensity of the vowel formants gains importance for vowel qualities at the boundary, such as those used by Chistovich. Her results make sense as a consequence of ANF rate adaptation (16) and indicate that the auditory representation of a stationary vowel-like stimulus changes as a consequence of the ANF adaptation. The experiment described in this chapter was designed to investigate whether auditory representations generated before discharge rate adaptation are better discriminated than the flattened auditory representations presumably generated after adaptation. The possible contribution of the synchronized ANF's responses is ignored here.

This discrimination experiment is similar to the formant frequency difference limen experiment carried out by Flanagan (1955). The rationale is that discrimination among complex stimuli, with the same type of spectral characteristics, directly reflects the sharpness of their auditory representations. Since discharge rate adaptation results in compression of the dynamic range of the ANFs, a reduction in the dynamic range of the auditory representation may be expected (fig. 13).

In the present series of experiments it is assumed that it will be possible to relate differences in discrimination performance to the quality of peripheral auditory

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16. I have run an informal control experiment to check for the onset effect. In that experiment (1981) I studied the masking level produced by a 1kHz tone as a function of the signal location using a simultaneous masking paradigm. I observed a masking level at the onset of the stimulation that was about 5dB higher than during the stationary portion of the masker. This difference between the onset and the stationary levels is smaller than that found by Chistovich (1971). I interpreted the difference as resulting from integration of that onset effect over the duration of the signal (20ms). I did not publish the results both because I was the only subject and no careful investigation of the possible masker and signal interactions was made.

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representations alone. This is a convenient assumption but may have limitations. In any case, the design of these experiments keeps factors like order and range effects, memory effects and attention under control. As to influences of training and linguistic backgrounds, my strategy was to use subjects with different degrees of experience and different native languages, on the assumption that individual bias will cancel out in the global results.

![Figure 13](image)

**Fig. 13** Estimated auditory representations before and after auditory-nerve fiber adaptation.

One way to study discrimination under adapted and non-adapted ANF’s response would be to study discrimination among long duration stationary stimuli and compare the performance with the discrimination among short duration versions of the same stimuli. The evident drawback with this method is that the durational difference between the stimuli for the adapted and non-adapted conditions makes it impossible to relate discrimination performance to the adaptation phenomenon alone.

![Figure 14](image)

**Fig. 14** Auditory-nerve fiber responses for abrupt and gradual onsets of stimulation. (From Delgutte, 1980, with permission of the author and publisher).

A better method can be developed from the fact that abrupt onsets of stimulation seem to produce less adaptation than gradual onsets (Delgutte, 1980) (fig. 14). In this
way it is possible to produce non-adapted and adapted responses keeping the duration of the stimuli constant and varying only their onsets. The total energy of the abrupt and the gradual onset stimuli can, therefore, be the same. In addition, the duration of the stimuli must be short so that the abrupt onset stimuli do not cause the ANFs to adapt. This is the method used in the present experiment.

2.2. Method

2.2.1. Stimuli

All the stimuli used in this experiment were brief and had a constant F-pattern. They were generated by exciting formant circuits with amplitude modulated pulse trains. The trains consisted of only 5 pulses. For the abrupt onset stimuli the pulses had exponentially decreasing amplitudes. For the gradual onset stimuli the pulses had exponentially increasing amplitudes. The frequency of the excitation pulses (F0) was kept constant during the whole stimulus and equal to 120Hz in all the cases. The formant circuits were implemented by a serial connection of four second order low-pass filters with bandwidths (Hz) given by \( B = 50 + 0.05x F \), where \( F \) is the formant frequency in Hz.

The pulse sequences had a 20dB amplitude difference between the first and the fifth pulses. The total duration of the excitation sequence was 33ms. The excitation pulses were rectangular and had a duration of .05ms.

![Source signal and output for the reference stimuli with abrupt and gradual onset.](image)

To obtain an adequate source spectrum, the pulse train was low-pass filtered by a first order low pass filter (100Hz) before the input of the formant filters (Fant, 1960). The formants were constant throughout the stimuli. Their frequencies were set at
F1=200Hz, F3=2600Hz, F4=3600Hz, while F2 was varied from stimulus to stimulus, assuming values between 1510Hz and 1690Hz, in 30Hz steps. Fig. 15 shows the source and the signal corresponding to the first stimulus (the "reference stimulus") for both the "abrupt" and the "gradual" onset series (i.e., for F2=1510Hz). By increasing F2 in 30Hz steps, two corresponding series of 7 stimuli were created, as schematically illustrated in fig. 16: one of the series of 7 abrupt onset stimuli, which differed only in their F2 values, and another series of 7 gradual onset stimuli, generated with exactly the same formant values as in the abrupt onset series.

The stimuli were generated digitally, by BLOD (17) and stored in files that were long enough to accommodate each of the stimuli without truncation (100ms files). To guarantee that the same pulse amplitudes would be delivered - in reversed order - for both the abrupt and the gradual series, the synchronization of the amplitude modulator and the pulse generator was carefully checked. The sampling frequency was 20kHz and each data point was a 16bit integer. The output was made via a 16bit D/A converter, at 20kHz. The anti-aliasing filter had a cut-off frequency of 8kHz, a measured attenuation of -72dB/oct, less than 1dB of ripple within the passband and a stop-band attenuation of 56dB (18).

![Fig. 16 Source and filter connections to generate the series of abrupt and gradual stimuli.](image)

To avoid distortion due to clipping of the peaks, a 1kHz tone, with a maximum amplitude 1dB above the highest amplitude peak in the stimuli, was used to calibrate the level for the whole chain - from the computer to the headphones.

The stimuli were presented via Sennheiser HD414 headphones at a nominal level of 76dBspl (100mVrms) for the 1kHz calibration tone. The maximum level deviation from the nominal 76dB SPL was 1dB, due to differences between the headphones used by subjects participating in group sessions.

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17. BLOD - Block diagram simulator, is a software developed by P. Branderud, Institute of Linguistics, University of Stockholm. It consists of modules simulating filters, generators, etc, that can be easily coupled to simulate block diagrams.

18. In some cases an anti-aliasing filter with a cut-off frequency at 6.3kHz was used. This filter has a better stop-band attenuation, about 12 dB below that of the 8kHz filter.
2.2.2. Procedure

The perception test followed the so-called non-adaptive, 2-Alternative Forced Choice (2AFC) paradigm, which consists in creating situations in which the subject is asked to choose one of two predefined alternatives. "Non-adaptive" means that the subjects were not informed, during the test, about the correctness of their choices.

In this experiment, the stimuli were presented in pairs containing a "reference stimulus", A, (either from the abrupt or from the gradual onset series) and another stimulus, X, drawn from the pool of 7 available stimuli (with the same type of onset as the reference). The subject's task was to judge for each (A,X) or (X,A) pair if the percepts of A and X were equal or not.

The stimuli in a pair were separated by a 350ms silent interval. This short silent interval was chosen so that the degradation of the first stimulus representation in the precategorical acoustic storage (PAS) would be reduced to a minimum (Crowder, 1982). Between consecutive pairs there was a 4s interval during which the subjects were supposed to make their similarity judgments. After the presentation of 14 pairs, a 10s pause was inserted to allow the subjects some rest and to let them know "where they were" in the test sequence.

Before the test proper, the subjects had a training session during which they were presented with all the pairs that would be used in the test proper. After a 40s break, the test session started. The stimuli pairs, both in the training set and in the test set, were randomized. A pair containing abrupt onset stimuli could be followed by a pair containing gradual onset stimuli, or vice versa, to minimize the effects of systematic learning during the tests (19).

To increase reliability, the test duration was only 12 minutes, including the training session. Total test duration was considered an important design variable to reduce stress, fatigue and attention effects.

![Fig.17 Illustration of the d' concept.](image)

19. A sequentially ordered presentation of the stimuli pairs would introduce undesirable context effects and possibly involve the subject's "discovery" of "expected" answers, seriously impairing the measurement of the difference limens. Although a random presentation tends to increase the background noise in the results, it has the crucial advantage of revealing difference limens that depend very little on context effects. The convenience of a random presentation may be further supported by Luce's theory: random presentation + 2AFC. (Luce, 1963; Luce and Galanter, 1963)
The discrimination scores were computed in terms of d' values in order to cancel out the effect of false alarms (20) (Thrustone, 1927; Sorkin, 1962). Fig. 17 gives an example of the calculation of d'. The distribution with the lowest mean value (on the left) is taken to be the distribution of the responses "same" and the one with the higher mean (right) that of the responses "different". Given the false alarm rate in a discrimination task among two stimuli, i.e., the percentage of responses "different" when, in fact, the stimuli were physically the same, it is possible to know how far from the mean of the distribution "same" the subject is placing the criterion. The percentage of responses "same" when the stimuli were actually physically different, enables the calculation of the position of the criterion relative to the mean value of the distribution "different". Since the criterion is applied simultaneously to both distributions (they overlap more or less) it is possible to determine the distance d' between these two distributions. It should be noted that although one may influence experimentally the false alarm and the hit rates, the d’ model assumes that the distance between the means of the two distributions is constant for a given stimuli set and a given subject (d’ is a measure of the subject's capacity to discriminate between two stimuli). If the subject is penalized for saying "different" when the stimuli actually are the same, he tends to move the criterion upwards reducing his false alarm rate at the cost of missing some of the real different stimuli but the d’ should remain unchanged. Conversely, a penalty for saying "same" when the stimuli are, in fact, different would make the subject cautious about answering "same".

The d' computation was made after pooling the results from all the subjects (Lacerda, 1986, 1987). The advantage of the d' measure is that it can be interpreted in terms of a distance between the listener’s representations of equal and non-equal percepts. In contrast to the direct use of the percentage of correct responses given by a particular listener, d' reveals the listener’s ability to discriminate among the stimuli in a way that is independent of the hit or false-alarm rate per se.

2.2.3. Subjects

All the subjects involved in the experiments were submitted to Bekesy audiometry and all had normal hearing thresholds. They had no reported or detected speech problems. The verification of the subject’s hearing threshold is relevant mainly from the point of view of the methodic control of the experimental variables. Otherwise, since the psychoacoustic phenomena that are being studied are expected to be involved in the normal perception of speech, any listener able to function in a purely auditive speech communication situation - like telephone communication - should be eligible as a subject for these perception experiments.

In this first perception test a total of 19 subjects listened to the brief, constant F-pattern stimuli and tried to discriminate among them (21). The training and language

20. "False alarm" is an incorrect "different" response. A correct "different" response is termed "hit".

21. The test was initially carried out with four subjects, in a group test session. The design of this first pass was slightly different from the other ones because the
backgrounds of the subjects were very different. The subjects were native speakers of Danish, English, Estonian, German, Portuguese and Swedish and in addition to their native languages, all of them were fluent speakers of both Swedish and English. The subjects were staff members and students of the Phonetics Department of the Institute of Linguistics of the University of Stockholm, Sweden. The experimenter took the test but was not counted as a subject in the final analysis.

2.3. Results

Fig. 18 shows the pooled discrimination results from all the subjects. The x-axis indicates the differences between the F2 of the reference stimulus and the other stimuli that were compared with the reference. The ordinate gives the d' values that were obtained for the dF2 differences indicated along the abscissas. Filled squares indicate discrimination scores from the abrupt onset stimuli and the filled circles show the scores from the stimuli that had a gradual onset of stimulation. The open circles display Flanagan's (1955) data (22).

![Figure 18](image-url) Discrimination scores for abrupt and gradual onset stimuli with periodic source. See table 1, appendix, for significance levels.

22. Flanagan's data was recomputed in terms of d' values, defining a constant false alarm rate from the percentage of wrong "different" judgments and using the correct "different" judgments as hit rate.
There is a clear increase in discrimination among stimuli with abrupt onset of stimulation. To check the significance of the discrimination scores across subjects, a t-test was run using the number of correct discriminations for each stimuli pair. The outcome of the t-test (related) indicated that the difference between the discrimination scores for abrupt and gradual onsets were significant (p<.05) for F2 differences of 60Hz and 90Hz.

The pattern displayed by the data points indicates that for small F2 differences the d' values are very small and similar for both abrupt and gradual onset stimuli. As the difference between the F2 of the reference and the other stimulus in the pair increase, the d' values increase with them. However, the data points from abrupt and gradual stimuli diverge when the differences between the F2 of the stimuli in a pair are of the order of 60Hz to 90Hz. In this region a significant advantage for the abrupt onset stimuli is observed. For further increases in the F2 differences, the abrupt and gradual data points fall close to each other again.

The differences in discrimination for abrupt and gradual stimuli vanish for very small or very large differences in the F2 of the stimuli that are involved in the pairs.

2.4. Discussion

The results of this experiment support the notion that the auditory representations based on non-adapted discharge rates are sharper than those generated after adaptation has taken place. The effect was most prominent for discrimination near the limits of resolution of the auditory system. The convergence of the data points from abrupt and gradual onsets for the two extremes of the range of F2 differences can be interpreted as a further indication that the effects observed for dF2=60Hz and dF2=90Hz are due to onset differences: for very small F2 differences, the discrimination scores are low regardless of the type of onset; for large F2 differences, abrupt onsets do not give any advantage because the stimuli are easy to discriminate anyway. The improved discrimination between auditory representations generated by non-adapted ANFs will be referred to by "onset effect".

The present results can be compared with those obtained by Flanagan (1955). Flanagan used long (750ms) steady-state vowels that in this perspective clearly generate adapted auditory representations. It turns out that his data (open circles) closely follow the data points obtained for the gradual onset stimuli in this experiment. Furthermore, the data from Nord and Sventelius (1979) - who used Flanagan's (1955) stimuli to study the possibility of predicting difference limens from spectral distance measures - also follows the data points from the gradual onset discrimination when converted to d' (23).

23. There are differences in the F1 frequencies of the current study and those of Flanagan and Nord and Sventelius. While F1 for the brief stimuli was fixed at 200Hz, the long vowel stimuli had F1=500Hz. The influence of the F1 value on the discrimination scores was not investigated and, as it was pointed out by Nord and Sventelius, phoneme boundaries may affect discrimination among the stimuli.
2.5. Summary and conclusion

The results of this experiment showed that stimuli with abrupt onsets were better discriminated than stimuli with gradual onsets. They can therefore be interpreted in support of the hypothesis that stimuli eliciting non-adapted responses of the ANFs are better discriminated than those producing adaptation of the nerve fibers. Since the aim of this thesis is to evaluate this effect in relation to the perception of speech, the next step is to investigate to what extent it is exploited under more speech-like conditions. This question will be addressed in the next experiment.
3. FREQUENCY DIFFERENCE LIMITS FOR CV AND VC SYLLABLES

3.1. Introduction

This experiment was designed to explore the possible consequences of ANFs' adaptation for the discrimination among speech-like sounds. In view of the previous experiment, the natural candidates to elicit non-adapted auditory representations are the classes of speech sounds having abrupt onsets of energy: stop consonants, ejectives, click sounds and affricates.

To set up an experiment like the one with the brief, constant F-pattern stimuli, another set of speech sounds capable of eliciting adapted ANF responses without introducing durational differences is required. If the stimuli are to be treated as speech sounds by speakers of most European languages, the choice is limited to CV and VC syllables, where the C stands for a stop-consonant drawn from /p,t,k,b,d,g/. Of this set, /d/ was selected because it can be synthesized without voice bar or release burst, with an initial F-patterns equal to those used in the experiments of the previous chapter. A vowel /a/ was chosen because it is possible to create a large variety of /Ca/ varying only the F2 onset frequency at CV boundary. It is expected that discrimination among CV utterances differing in their initial F2 values might be assisted by the non-adapted ANF responses at the onset of stimulation. For VC utterances, differing in their final F2 values, discrimination is expected to be based on adapted ANF responses.

3.2. Method

3.2.1. Stimuli

The stimuli for this experiment were CV and VC syllables, namely /da/ and /ad/ synthetic utterances. The /a/ vowel was the same in all cases and the CV and VC differed only in their F2 values at the consonant/vowel transition (24).

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24. The term "locus" was used in earlier reports of these experiment (Lacerda, 1986, 1987) to refer to the actual formant pattern at the first excitation pulse (initial locus of a CV utterance) or at the last excitation pulse (final locus of a VC utterance). That use of the term "locus" is not the same that was proposed by Delattre, Liberman
The advantage of these CV and VC syllables is that the relevant differences between the utterances are present at the first and at the last excitation pulse, respectively. In order to be able to discriminate among /da/ utterances, the subjects must rely on the auditory representation of their onset F-patterns (ONFPs). Similarly, to discriminate among /ad/, the subjects have to make use of the auditory representation of the offset F-patterns (OFFPs).

To be able to compare discrimination based on the onsets of /da/ utterances with that based on the offsets of /ad/, it is convenient to generate /da/ and /ad/ stimuli that are mirror images of each other.

In order to have full control over the spectral characteristics of the stimuli, all the CV and VC syllables were generated synthetically. Furthermore, to guarantee symmetry between the CV and the VC syllables, a strong open phase effect was simulated so that the ringing due to the formant filters would vanish rapidly, favoring a symmetrical pattern for CV and VC in spite of the opposite movements of the formant transitions. In addition, the synchronization between the pulse generator and the control circuit that generated the formant transitions was carefully controlled so that the excitation pulses would be delivered for exactly the same formant values, both during the CV and the VC transitions.

A preliminary test with 200ms long /da/ and /ad/ stimuli showed that increasing F2 in steps of 30Hz produced /da/ stimuli that were too difficult to discriminate. Only towards the end of the range could any consistent discrimination results be obtained. Also, the long, static /a/ vowel produced such a large memory load that discrimination largely improved with the reduction of the vowel’s duration.

The /da/ stimuli were generated by producing appropriate formant transitions between ONFPs having the same formant frequencies (except for F2) as were used in the previous experiment and a target /a/ vowel. The actual formant frequencies at CV or VC boundary were F1=200Hz, F3=2600Hz, F4=3600Hz, while F2 assumed values between 1450Hz and 1750Hz, in steps of 50Hz. This new F2 range includes the range used in the previous experiment. The vowel formants were set at F1=750Hz, F2=1250Hz, F3=2400Hz and F4=3050Hz. The transitions between the ONFPs and the target vowel were exponential with maximum slope at the onset. These transitions had 90% of their total range within the 50ms duration of the stimuli. In the case of the VC syllables, to guarantee symmetry between the CV and the VC stimuli, the transitions started at 90% of what would be their total excursion and ended at the prescribed OFFPs.

and Cooper (1955), where locus was an abstract convergence point for the formants that was supposed to be characteristic for each stop consonant. To avoid the redefinition of the term, I will use "onset F-pattern" (ONFP) and "offset F-pattern" (OFFP), instead.
The stimuli resembled natural, fast, /da/ and /ad/ utterances. Since one of the goals of the experiment was to study how discrimination was affected by non-stationary formant patterns, they were generated without voice bar or explosion bursts.

3.2.2. Procedure

This perception experiment was carried out in the same way as the previous one. Here too, a 2AFC non-adaptive paradigm was used. The stimuli were presented in a (A,X) and (X,A) format, where the a reference stimulus A was the /da/ or the /ad/ that had the lowest F2.

Each pair contained either /da/ or /ad/ utterances. The stimuli pairs were randomly drawn from the pool of both /da/ and /ad/ pairs and the subjects were simply asked to discriminate among the stimuli in the pairs. No instructions were given about how to listen to the stimuli.

The experiment was run in an anechoic room. To achieve the best possible signal-to-noise ratio, the stimuli were directly read, at 20kHz, from the computer files via a 16bit D/A converter followed by a 6.3kHz anti-aliasing filter. They were transmitted to the anechoic room via balanced cables, differentially amplified and finally delivered to the subject via calibrated Sennheiser HD414 headphones. The subjects gave the responses on an answer form and no feedback was provided. The test proper was preceded by a training session during which all the stimuli pairs were presented. The total test duration was about 15 minutes.

3.2.3 Subjects

15 subjects participated in this test. They all fulfill the same requisites as those involved in the previous experiment (having normal hearing with no reported or detected language problems). The group was not homogeneous in terms of their experience with perception tests. 3 of the subjects had participated in the previous experiment.
3.3. Results

The discrimination scores from the /da/ and /ad/ stimuli are plotted in fig. 19. There are, at least, two salient aspects in these results, namely
1) the considerable drop in the discrimination scores from CV and VC utterances as compared to discrimination among the brief, constant F-pattern stimuli; and
2) the fact that CV utterances were less easily discriminated than their VC counterparts.

![Discrimination scores for /da/ and /ad/.](image)

Fig. 19 Discrimination scores for /da/ and /ad/. See table 2, appendix, for significance levels.

After each run, the subjects were asked how sure they were about their discriminations and what their strategy had been. The subjects consistently reported that it was easier to discriminate among /ad/ than among /da/. Some subjects tried to interpret the different /da/ and /ad/ stimuli as more or less palatalized /d/. Evidently, this is in agreement with the obtained discrimination scores. A one-tailed t-test (related) showed that the advantage of discrimination among /ad/, in relation to that among /da/ was very significant (p<.01) for all the F2 differences (dF2) greater than 100Hz, except for dF2=200Hz, which was significant at p<.025.

For more details on statistical results, see the tables in the appendix.
3.4. Discussion

The results of the experiment with the brief, constant F-pattern stimuli were compatible with the above hypothesis, which was based on both Chistovich's (1971) and Delgutte's (1980) findings. That hypothesis was that the auditory representation of the initial part of a stimulus should be relatively sharp because it was based on discharges of non-adapted ANFs. However, the results of the present experiment using CV and VC syllables are puzzling in the light of the onset effect: on the one hand the discriminability among the stimuli is quite poor; on the other, it was not those stimuli in which the relevant spectral differences were delivered at the onset of stimulation that were best discriminated, but rather those differing in their OFFPs.

To offer an explanation for the observed degradation of discriminability among CV or VC syllables as compared to discrimination among the brief, constant F-pattern stimuli, the small differences in the durations of the two sets of stimuli is unlikely to be a cause for the discrimination differences.

On the one hand, the absence vs presence of formant transitions in the two sets might explain at least part of the difference. The reason is that the formant transitions present in the latter set of stimuli make them more speech-like. Thus, all the /da/ and /ad/ stimuli would be perceived as members of the same category of "dental place of articulation", resulting in well known poor within category discrimination (Liberman, Harris, Hoffman and Griffith, 1957; Liberman, 1982). It could, therefore, be argued that whereas the subjects discriminate among the brief, constant F-pattern stimuli on a purely psychoacoustic basis, the more speech-like stimuli are processed in a special "speech mode", that is less directly dependent on purely psychoacoustic processing (Studdert-Kennedy, 1982). In other words, listening to speech in the "phonetic mode" (Liberman, Isenberg and Rakerd, 1981) would go beyond a mere psychoacoustic integration of auditory information (McGurk and MacDonald, 1976; Warren, 1970; Pols and Schouten, 1978).

An interesting alternative explanation for the /da/-/ad/ experimental results is to account for them in purely psychoacoustic terms. This alternative explanation involves what called Howell and Rosen (1984) "auditory sensitivities". The basic assumption is that psychoacoustic processing of auditory stimuli must underlay phonetic processing. The capacity to discriminate among different sounds is the ultimate constraint for how close two speech sounds that are to be treated as different phonemes can be. Two sounds cannot be treated as different phonemes if they cannot be auditorily discriminated during the learning stage. What happens after the acquisition of a native language may be a different matter. It is obvious that if languages made full use of the difference limens to define sound distinctions, their phonemic spaces they would be so crowded that discrimination would be too critically dependent on environmental conditions. The solution of increasing the tolerance of the classification grid by reducing the number of categories that have to be separated seems to have been adopted by natural languages, along with the listeners becoming the discrimination of relevant contrasts in their native language.
Natural auditory sensitivities, as they are regarded here, limit the proximity of two phonemes of a language during the language acquisition stage. The process of language acquisition optimizes these innate sensitivities for communication efficiency. In consequence, whenever subjects are asked to make judgments about speech-like stimuli, the "acquired speech sensitivities" will color the judgments to an extent that is related to the language experiences of the subject (Mochizuki, 1981; Eimas, 1975; Miyawaki, Strange, Verbrugge, Liberman, Jenkins and Fujimura, 1975).

For an auditory explanation of the /da/-/ad/ discrimination scores, the different language backgrounds of the subjects have to be considered but since /d/ and /a/ belong to the phoneme inventories of the native languages of all these subjects, it can be assumed that linguistic background produces the same influence on all the individual scores. The auditory explanation for the obtained discrimination scores uses the non-stationariness of the CV and VC stimuli in a way that differs from that of the proponents of the "phonetic mode" of speech perception. Rather than say that the movement of the formant transitions make the stimuli speech-like and that is the reason for their poor discrimination, I propose an auditory explanation. The auditory representations of the formants generated by the ONFPs produce sensory smearing over neighboring auditory channels that is caused by the rapid formant transitions before adaptation has had time to occur. The ONFP and the initial part of the transition produce, therefore, a "blurred" auditory pattern decreasing the discriminability among the CV ONFPs. Similarly, the VC OFFPs are also affected by the transition movements. The transition is delivered after adaptation of the ANFs. However, the rapid transition movement out of the adapted channels may lead to the generation of onset effects towards the VC OFFPs. An important difference, compared to the auditory processing of the CV ONFPs, is that for VC OFFPs the sensory smearing does not have as much influence on the auditory representation of the OFFPs. This is a mere consequence of the temporal sequence of the excitations produced by the CV and VC utterances. Because of this reversal of the excitation sequence, the last excitation pulse of a VC utterance - the one conveying the most relevant OFFP information for the discrimination among /ad/ - produces an auditory representation that is not subsequently disturbed by new "off-tune" patterns. The residual excitation in the auditory channels that is produced by the VC OFFPs, is not disturbed by new, competing auditory patterns. It therefore seems reasonable, within a purely auditory approach, that the VC utterances are better discriminated than their mirror CV mirror images.

The advantage of VC OFFPs must be further investigated as it is in apparent contradiction with the well known results from other discrimination tests with clipped CV and VC utterances (Krull, 1983; Pols and Schouten, 1978; Schouten and Pols, 1984) as well as with the results obtained by Sidwell and Summerfield (1986), for discrimination among symmetrical /b/, /d/ and /g/ in CVC utterances generated with noise excitation.
4.0. CV AND VC DISCRIMINATION: ROLE OF TRANSITION RATES

4.0.1. Introduction

The outcome of the experiment with the CV and VC syllables was unexpected, if only the onset effects are considered. The CV syllables could be expected to be better discriminated than their VC counterparts, but this was not the case. It seems however that it may be possible to explain the results by considering not only the onset effects but also the consequences of sensory smearing of the spectral information delivered at the CV ONFPs along with the effect of residual excitation provided by the VC OFFPs. In fact, it may be that the relevant F2 information of the ONFP is smeared because of the transition movement before adaptation of the ANFs has had time to occur. This may produce a blurring of the F2 auditory representation. In contrast, the F2 information in the VC OFFPs, present in the residual excitation, is relatively undisturbed. To investigate the explanatory power of these two additional effects it is necessary to manipulate the conditions under which the onset and offset auditory patterns are generated. This is the matter addressed by the present section.

According to the sensory smearing hypothesis, reducing the transition rate just after the CV ONFP will increase the accuracy of its auditory representation by reducing the amount of blurring. On the other hand, the residual excitation hypothesis does not lead to any improvement of the discrimination scores as a result of lowering the transition rates at the VC OFFPs.

To test these hypothesis, two new experiments were designed. In one of them the CV ONFPs were "stabilized" by holding the ONFP during a few excitation pulses before the onset of the transitions. In the other, the VC OFFPs were "extended" by delivering a few extra excitation pulses, while keeping the OFFP. The study of the residual excitation hypothesis will be reported first.
4.1. ROLE OF RESIDUAL EXCITATION IN VC DISCRIMINATION

4.1.1. Introduction

To evaluate the hypothesis that the relatively good discrimination among /ad/ might be due to residual excitation in the channels to which the VC OFFP was delivered, a new experimental situation was created by simply extending the OFFPs. If the auditory system assesses the residual excitation produced by the VC OFFPs, then extending the OFFPs - suffixing - should not alter discrimination performance because the relevant information for discrimination was already present in the residual excitation patterns.

4.1.2. Method

4.1.2.1. Stimuli

The stimuli for this experiment were constructed by appending to each /ad/ OFFP three extra glottal pulses while keeping the formant values of the OFFP. The duration of this suffix was 25ms. The formant transitions were linear in this experiment. A series of seven /ad/ stimuli, differing only in the F2 values of their OFFPs, was generated by computer simulation. The stimuli were recorded in files which were subsequently read during the perception test. The reference stimulus had its OFFP at F1=200Hz, F2=1450Hz, F3=2600Hz and F4=3600Hz. The F2 value for the OFFPs of the other six stimuli in the series was first 1550Hz (100Hz increase) and thereafter, from 1600Hz to 1800Hz, in increments of 50Hz. The vowel formants were F1=750Hz, F2=1250Hz, F3=2400Hz and F4=3050Hz for all the stimuli.
4.1.2.2. Procedure

The format of the perception experiment was again a 2AFC (see section 2.2.2). The task consisted of judging whether the two stimuli in an (A,X) or (X,A) pair were the same or not. A stands for the reference stimulus and X for any stimulus of the series. The interval between the stimuli in a pair was 350ms. The interval between consecutive pairs was 4s. A 10s pause was included after each group of 14 pairs.

The subjects were simply asked to discriminate among the stimuli in each pair. Any references to the possible speech-like quality of the stimuli were intentionally omitted from the instructions. The stimuli were presented via Sennheiser HD414 headphones and the subjects performed the task in individual sessions in an anechoic room. The stimuli were presented on-line from the computer to achieve the best possible signal-to-noise ratio. The equipment was the same as referred to in the previous chapter.

4.1.2.3. Subjects

As was the case for the previous experiments, the 13 subjects that participated in this perception test were members of the staff and students of the Institute of Linguistics of Stockholm University. None of the subjects had reported or detected hearing or speech problems. Most of the subjects had already been involved in at least one of the above reported experiments.

4.1.3. Results

The discrimination scores for the "suffixed" /ad/ stimuli were plotted as filled circles on fig. 20. For comparison, the discrimination scores from the previous,
non-suffixed, /ad/ stimuli are also shown as unfilled circles. For ease of reference, the suffixed stimuli were named /ad*/.

Fig. 20 Discrimination scores for suffixed /ad*/ (25ms) stimuli. See table 4, appendix, for significance levels.

The discrimination scores for /ad*/ evolve in much the same way as those from /ad/, in the previous experiment. See appendix with significance analysis.

4.1.4 Discussion

The discrimination scores obtained in this experiment did not change significantly when the OFFPs were prolonged, relative to those of the previous experiment. Thus, the results support the hypothesis that discrimination among the original /ad/ stimuli was assisted by the residual excitation produced by the OFFPs.

The hypothesis that the residual excitation may have a part in discrimination among /ad/, is in accordance with the basic neurophysiological facts underlying the general approach taken in this thesis. ANFs do not immediately recover after having been excited (Kiang et al., 1965; Harris and Dallos, 1979; Smith, 1979; Smith and Brachman, 1980; Cooke, 1986). As mentioned above, that has also been observed for the auditory-nerve representation of speech-like sounds (Delgutte, 1980; Sachs and Young, 1979; Sachs Voigt and Young, 1983). In modeling studies (Delgutte, 1982) of the processing of speech sounds, the auditory channels that have been stimulated by preceding sounds do not respond in full to new stimulation until a certain period of time has elapsed.

The possibility of assessing the residual excitation produced by the OFFPs is also compatible with psychoacoustical studies demonstrating the existence of post-stimulatory effects (Zwicker, 1964; Wilson, 1970; Houtgast, 1974; Summerfield et al., 1984). The durations and the stimulation levels produced by the VC stimuli are obviously much lower than those typically used in forward masking experiments. However, the longer durations used in psychoacoustic experiments are motivated by
the demand for clear effects. In a discrimination task, like in these VC perception tests, it is reasonable to admit that any just noticeable difference between the stimuli will suffice.

It would thus seem as if all available evidence supports the hypothesis forward in this section: the observed discrimination patterns for the VC stimuli are based on residual masking of their OFFPs.

4.2. ROLE OF SENSORY SMEARING IN CV DISCRIMINATION?

4.2.1. Introduction

The experiment reported in this section was designed to test the hypothesis that the relatively low discriminability among the /da/ stimuli was caused by sensory smearing of the relevant ONFP information. The basis for the sensory smearing hypothesis is the fact that the ANFs cannot adapt instantaneously. The initial assumption that only the ONFP would be sharply represented may be incorrect because the formant transitions rapidly glide out of the channels excited by the CV ONFP when the transition rate is high. For this reason, the discrimination scores among the different /da/ stimuli should improve as the transition speed is decreased.

4.2.2. Method

4.2.2.1. Stimuli

The stimuli for this experiment were manipulated /da/ utterances. Instead of directly reducing the transition speed, the ONFP was preceded by a prefix that had the same F-pattern as the CV ONFP. The prefix consisted of a few excitation pulses that were delivered while keeping the formant filters at the ONFP values. After the specified prefix duration, the formant values evolved towards /a/, with linear transitions.

As in the preceding experiments, the stimuli were organized in series of seven stimuli that differed only in terms of the specification of their F2 ONFP values (25).

25. Note that since the vowel target is held constant, changes in the F2 ONFP value necessarily result in changes of the transition speed of F2.
There were three different prefix durations: 16.6ms, 25ms and 33.3ms corresponding to 2, 3 and 4 glottal pulses that were delivered before the onset of the formant transitions. For each prefix duration a series of seven stimuli was generated. The reference stimulus of each series had an ONFP pattern specified by F1=200Hz, F2=1450Hz, F3=2600Hz and F4=3600Hz. The only difference between the reference and the other six elements of each series was the F2 ONFP value. The F2 frequency difference between the reference stimulus and the next element of the series was 100Hz (F2=1550Hz). Thereafter F2 was increased in 50Hz steps, up to 1800Hz. The vowel was defined, in all the cases, by F1=750Hz, F2=1250Hz, F3=2400Hz and F4=3050Hz. These were the final values of the linear formant transitions. The duration of the transitions was the same for all the series.

4.2.2.2. Procedure

As before, the perception tests were run using a non-adaptive 2AFC paradigm, without feedback. The stimuli were presented in (A,X) or (X,A) pairs, where A denotes the reference element of a series and X any element of the same series. The subjects were asked to judge whether the two elements in a pair were identical or not. No instructions were given about what to listen to in order to perform the task. All the subjects had an initial training session during which they were presented with all the possible pairs that would occur in the test proper. The test sessions were run with one subject at a time. The subject sat in an anechoic room and listened to the stimuli, that were presented on-line from the computer, via calibrated Sennheiser HD414 headphones.

The discrimination between the 25ms prefix /da/ was done in the same test session of the 25ms suffix /ad/. The discrimination between the 16.6ms and the 33.3ms prefix /da/ was tested in a new session.
4.2.2.3. Subjects

The discrimination between the stimuli with 25ms prefixes was done by the same 13 subjects who had participated in the previous experiment. The perception tests with the other prefix durations were run with 15 subjects (2 new subjects participated in this experiment).

4.2.3. Results

The discrimination scores are presented in fig. 21. The plot shows d' values, pooled from all the subjects, as a function of the F2 differences between the reference stimulus and the other stimuli in the series. The different curves correspond to the different prefix durations, including the original "zero prefix" situation that is indicated by the dotted line. The general trend is that discrimination improved with the introduction of the constant F-pattern prefixes.

Fig. 21 Discrimination scores for the prefixed /da/ stimuli. Each curve displays discrimination for a given prefix duration. See tables 3 and 4, appendix, for significance levels.
To show the effect of the prefix duration on the discrimination scores more clearly, the data were replotted in fig. 22 where d’ values are shown as a function of the prefix duration. The parameter for this new plot is the F2 frequency difference between the reference A and the stimuli X. An interesting effect that is apparent from this plot is that discriminability does not increase monotonically with the duration of the prefix. Rather, it clearly reaches a maximum for the 16.6ms prefix. Another aspect of these results is that the amount of improvement produced by the prefix depends on the F2 frequency differences between the stimuli. See appendix with significance analysis.

![Graph showing discrimination scores for /da/ stimuli as a function of the prefix duration.](image)

Fig.22 Discrimination scores for /da/ stimuli as a function of the prefix duration. Each curve shows the scores obtained for a constant dF2. See tables 3 and 4, appendix, for significance levels.

4.2.4. Discussion

The results of this experiment are clearly compatible with the sensory smearing hypothesis. The results are predicted by the hypothesis because preceding the CV ONFPs with a constant F-pattern prefix resulted in a general improvement of the discrimination among /da/.

A significant feature of the results displayed in fig. 22 is that discrimination did not increase monotonically with the duration of the prefixes. Instead, the discrimination scores attained their maxima for a prefix duration of 16ms. Keeping the constant F-pattern prefix longer than 16ms did not improve the discrimination scores. Rather, discriminability was reduced, as the prefix duration was increased.

From the pattern of evolution of the d’ scores as a function of the prefix duration, it may be hypothesized that the auditory system uses a time-window of the order of 16ms for the representation of time-varying formant patterns. In fact, this window is of the same order of magnitude as the decay-time of the ANFs’ responses, just after the onset of stimulation. It seems probable that the 16ms time-window is related to the time it takes for an ANF to adapt to the stimulation level. If the formant frequencies
start changing after the initial 16ms, then new, fresh, ANFs will be engaged in the representation and blurring is likely to occur.

According to the results displayed in fig. 22, the influence of the onset of the transitions is greater for small F2 differences between the reference and the X stimulus (e.g. dF2=150Hz and dF2=200Hz). This can be explained by the relative importance of sensory smearing in terms of the discrimination task. The same amount of blurring produces much more discrimination errors if the differences to be detected are small than if they are large. Along this line, it may be asked why the discrimination scores for larger dF2 drop when the prefix duration is about 33ms. A possible reason is that this decrease in the discrimination may be related to blurring as well. If the ANFs adapt during the 33ms prefix, the formant transition will be enhanced as the formant moves out of the adapted channel and excites ANFs at rest. This explanation is compatible with available observations made on the discharge-rate adaptation of ANFs (e.g. Delgutte, 1980) and with predictions of discharge rate based on auditory models (e.g. Cooke, 1986). Unfortunately neurophysiological data on actual discharge patterns measured at CV onsets (Sachs, Young and Miller, 1982, p.126) were gathered using too large integration times to enable tracing the evolution of the discharge rate during the transition itself.

The perception results just discussed have important consequences in terms of the traditional categorical perception effects (Liberman, Harris, Hoffman and Griffith, 1957). These results show that discrimination within a category can actually be manipulated, at least for /da/ stimuli.

It should be noted that the range and frequency effects discussed by, for example, Parducci, (1965) and Rosen, (1979), which can explain some of the categorical perception phenomena are not relevant here. There is no question about the role played by range effects in the categorization of stimuli in a continuum. As Rosen and Howell (1981) demonstrated, the placement of the boundary between two categories - "pluck" and "bow" sounds in their experiment - depends on the range of stimuli used. However, no such effect can be used to explain the differences in the discrimination scores observed for these stimuli. It is not possible that, due to range effects, the stimuli of these series might have been classified into different phonemic classes. The range was, in fact, extended by 50Hz, from the non-prefixed to the prefixed stimuli, but the latter have all the same range of variation of F2. They only differ in the extension of their prefixes. The differences in the discrimination scores must, therefore, be attributed to the influence of the constant F-pattern prefixes. In other words, no change in phonemic labeling of the stimuli was observed, but nevertheless discrimination varied.
5. EFFECTS OF THE SOURCE IN FREQUENCY DISCRIMINATION

5.1. Introduction

The experiment to be reported in this chapter investigates the possible role that the voice source might play for discrimination.

The fact that the /da/ utterances of the experiment in ch.3 were less well discriminated than /ad/ utterances, is in apparent conflict with data from other discrimination experiments with CV and VC utterances. While the conflict with data from natural utterances (e.g. Krull, 1983) may be explained by the commonly observed higher variability in VC OFFPs than in CV ONFPs (Lindblom and Lacerda, 1985), the results obtained with synthetic utterances are difficult to explain. In particular, the recent findings by Summerfield, Foster, Tyler and Bailey, (1985) indicating that the CV halves of CVC symmetrical utterances were better discriminated than the final VC are in direct conflict with the data in ch. 3.

There are two main differences between the stimuli used by Summerfield et al. and the stimuli of the CV and VC experiments that were reported in the previous sections. One is a durational difference - Summerfield et al.’s stimuli were VCV utterances, much longer than the /da/ and /ad/ stimuli. The other concerns the fact that in their experiment they used noise source excitation while for the /da/-/ad/ stimuli the excitation was produced by a periodic source with constant pitch.

This conflict between the results obtained by Summerfield et al. and the /da/-/ad/ stimuli demands an investigation of the possible role that the source might play for discrimination. Furthermore, it is important to know if the onset effect is dependent on the source characteristics, since the experiments by Carre and Quach-Tuan (1986) suggest that discrimination may be affected by the stimuli’s fine structure. Finally, another reason to study discrimination among noise excited stimuli is to reach a better understanding of the role of the stop-consonant release bursts in discrimination among natural CV syllables.
5.2. Method

4.2.1. Stimuli

The stimuli for this experiment were similar to the brief, constant F-pattern stimuli described in ch. 2, except that the periodic source was substituted by a noise source.

The stimuli were organized in two series of seven elements each. One series of abrupt onset stimuli for which the noise source was multiplied by a decaying exponential function giving a -20dB difference between its onset and offset. The series of gradual onset stimuli was generated using an increasing exponential function that produced a +20dB difference from its onset to the offset. The first element of each series was the reference stimulus, with formant frequencies at F1=200Hz, F2=1510Hz, F3=2600Hz and F4=3600Hz. The other six stimuli of each series were obtained by varying F2 in equal steps of 30Hz, from 1540Hz up to 1690Hz.

The use of noise excitation in these brief stimuli introduces a stability problem that does not arise with periodic sources. Since the noise source is only active during a 30ms time interval, stationariness of the noise source cannot be guaranteed. On the other hand, in order to test the effect that the onset characteristics of the stimuli might have in frequency discrimination, the fine time structure of the noise source has to be controlled so that abrupt and gradual onsets might be defined a priori. Given these design constraints, a segment of white noise was recorded in a file and used afterwards as a pseudo-noise source to generate the stimuli. In this way it was possible to create a situation comparable to that of the periodic excitation. The samples describing the fine time structure of the noise were the input to the amplitude modulation circuits. The segment of noise in the source file was taken at random from the output of the noise generator but it may not be representative of white noise. In terms of the properties of the source alone, the ideal situation would be to use a white noise generator but the statistical properties of white noise arise only when either long time averages or many independent, time-limited samples are considered. The present case fulfills none of these requirements but given the design constraints of this experiment, no other solution presents itself.
5.2.2. Procedure

This perception test was organized in the same way as the experiment in ch. 2. See section 2.2.2., for details.

5.2.3. Subjects

As for the other experiments, the 23 subjects for this perception test were normal hearing adults without any detected or reported language problems. They had different degrees of experience in perception tests and some of them had participated in previous experiments in this series.

5.3. Results

The discrimination scores obtained in this experiment are displayed in fig. 23. The discrimination differences that had been observed between abrupt and gradual onset stimuli, with periodic excitation source have now disappeared. There are only two small but significant differences (p<.05) for $dF_2=120\text{Hz}$ and $dF_2=180\text{Hz}$.

Fig.23 Discrimination scores for abrupt and gradual onset stimuli with noise excitation. See table 5, appendix, for significance levels.
The comparison between the results in ch. 2.3 and the corresponding discriminations of this experiment, show no significant differences, except for one case. For $dF_2=60\text{Hz}$, there is a significant advantage of the periodic source abrupt onset pairs over the corresponding pair with noise excitation. See appendix with significance analysis.

5.4. Discussion

The most salient aspect of these discrimination results was that the advantage of the discrimination among abrupt onset stimuli in ch.2 has now desappeard. Given this outcome, there are two questions that appear central:

1) Can source characteristics explain the differences between the results from periodic and noise sources, as proposed by Carre and Quach-Tuan (1986)?

2) How can the outcome of the last experiment be compatible with Delgutte’s (1980) data?

The first question deals with the alternative explanation for the discrimination differences suggested by Carre and Quach-Tuan (1986).

According to these authors, discrimination among stimuli generated with noise source does not depend on the type of onset characteristics because white noise excitation provides a good description of the formant circuits’ transfer functions for both abrupt and gradual onset stimuli.

Their argument relies on the perceptual effect of the transient generated by an abrupt onset of the periodic excitation. An abrupt onset of excitation delivered at the input of the formant circuits produces a transient with a broad band spectrum capable of generating a good transfer-function description of the formant filters. In their reasoning, the gradual onsets of stimulation do not produce initial transients and consequently poorer descriptions of the formant filters’ transfer functions are generated with gradual onsets. As a consequence, noise excitation should produce about the same discrimination results for both abrupt and gradual onsets.

Carre and Quach-Tuan’s (1986) tentative explanation is the result of a perception experiment designed to study the effects of non-stationary characteristics on the perception of vowels. Their stimuli were obtained using two different configurations of voice source, amplitude control and formant filters. In one configuration, the amplitude control circuit was inserted between the voice source generator and the formant circuits. In the other, it was placed after the formant circuits.

For the first configuration, the abrupt onset of stimulation will excite the formant circuits with a broad band transient, providing a complete description of the filter’s transfer function. For the second configuration, the transient produced by the onset of the amplitude control is not filtered by the formant circuits and therefore no complete transfer function can be obtained at the onset. The filter description provided by these stimuli is the line spectrum available during the stationary regime.

The results of their experiment showed that, when subjects were requested to choose between two vowel phonemes differing in openness, the stimuli generated with the first configuration always lead to a higher percentage of more "open vowel"
responses than the stimuli generated by the second configuration, with the same F0 and F1 values.

Carre and Quach-Tuan interpreted their results as an indication that subjects used the information available in the transient filter response generated by the first configuration. They suggested that the impulse response generated by this configuration enhances the high frequencies and therefore more "open vowel" responses are obtained in this case.

However, this line of explanation may not be applicable to the case of the discriminability among stimuli with abrupt and gradual onsets. The main reason is that transient effects like those invoked by Carre and Quach-Tuan are present in both abrupt and gradual onset stimuli as the periodic voice source used to generate them is simply time-reversed between the two series of stimuli. As it seems, transient effects, in Carre and Quach-Tuan’s sense, cannot explain the fact that almost no significant changes were found between abrupt and gradual onsets, with noise excitation.

Concerning the second question, the results now obtained could apparently not be predicted on the basis of the neurophysiological data available from Delgutte (1980). His measurements were made using abrupt ("CH"-like sounds) and gradual noise onsets ("SH"-like sounds) and clearly show an initial peak in the discharge-rates for the abrupt onset stimuli. The current results can be explained in neurophysiological terms if noise excitation produces less rate adaptation than periodic excitation. However, taking into account the type of connections between ANFs and the hair cells (Spoendlin, 1974), Delgutte’s measurements can be compatible with the outcome of this experiment. Since Delgutte’s measurements were made from an ANF connected to an inner hair cell, they reflect the response of one frequency channel to different onsets of noise. The ANF’s response may be similar to the response the fiber would give to one of the harmonics of a periodic, complex sound. This would explain the good match between his data and the results with the brief, constant F-pattern stimuli with periodic excitation. Nevertheless, when noise excitation is used, the contributions coming from the ANFs connected to the outer hair cells may become important because they respond to stimulation present at neighboring outer hair cells. The auditory patterns generated by noise excitation can therefore be different from those generated with periodic excitation and yet the response of a single ANF connected to an inner hair cell be the same.

A final remark should be added, considering the fact that the noise sample used in the experiment may be not representative of a white noise source. The use of the same sample of noise in the generation of all the stimuli may have introduced effects that critically depend on that particular sample. To increase the reliability of the experimental results, the stability of the discrimination data should be tested using new series of stimuli produced with other samples of noise. By doing this the situation of excitation by random white noise is approached via an ensemble average. This particular point was not investigated here but must certainly be considered in future experiments.
6. CAN /da/-/ad/ DISCRIMINATION BE GENERALIZED?

6.1. Introduction

Experiments with sweep tones and rapid formant transitions suggest that the auditory system may treat differently formant transitions of increasing or decreasing frequency (Pols and Schouten, 1982, 1987; Schouten, 1985, 1986). Also masking experiments seem to indicate that rapid upward and downward frequency sweeps generate different masking patterns (Lacerda and Moreira, 1982). In view of this and the possibility that formant frequency extrapolation effects (Heinz, Lindblom and Lindqvist, 1967; Lindblom and Studdert-Kennedy, 1967) might occur for the /da/ and /ad/ stimuli (ch. 3), it is interesting to study how the direction of the F2 transitions may influence CV and VC discrimination. Therefore, this chapter deals with an investigation of whether the discriminatory advantage of the /ad/ stimuli is related to the upwards trajectory of the F2 formant transition. To this end a new set of experiments was run using /ba/ and /ab/.

6.2. Method

6.2.1. Stimuli

The stimuli for this experiment were similar to the /da/-/ad/ described in ch.3.2.1. Two series of seven stimuli were created. One series of /ba/ utterances and another of symmetrical /ab/ utterances, like in the experiment of ch.3. The target vowel was defined by $F_1=750\, \text{Hz}$, $F_2=1250\, \text{Hz}$, $F_3=2400\, \text{Hz}$ and $F_4=3050\, \text{Hz}$. The ONFP and the OFFP of the reference stimuli were defined by $F_1=200\, \text{Hz}$, $F_2=950\, \text{Hz}$, $F_3=2200\, \text{Hz}$ and $F_4=2700\, \text{Hz}$. The other six stimuli of the series differed from the reference in terms of their ONFP and OFFP F2 values, which were incremented in equal steps of 50Hz. Just as for the /da/ and /ad/ stimuli, open phase simulation was used to obtain good symmetry between the CV and VC stimuli. The fundamental frequency of the voice source was constant and equal to 120Hz for all the utterances.
6.2.2. Procedure

As was the case in the other experiments, a non-adaptive 2AFC paradigm without feedback was used.

The stimuli were presented in (A,X) and (X,A) pairs containing two instances of either /ba/ or /ab/. Each pair contained the reference stimulus, A, and another randomly selected stimulus, X, drawn from the set of all the seven stimuli belonging to the series of the reference. Each of the 28 (2x2x7) pairs so obtained was repeated 5 times. The resulting 140 pairs were randomly organized in groups of 14 pairs. Within each pair, the stimuli were separated by a 350ms silent interval. The pause between consecutive stimuli in a group was 3.5s. Between groups there was a 10s pause.

The subjects participated in the test in individual sessions, carried out in an anechoic chamber. The stimuli were directly read from computer disk files and presented via calibrated Sennheiser HD414 headphones. The details of the transmission link between the computer and the headphones were described in ch. 2.2.2.

6.2.3. Subjects

This experiment was run with only four adult subjects with normal hearing. These subjects had already participated in other experiments in this series.

6.3. Results

The discrimination scores obtained for the /ba/ and /ab/ utterances are shown in fig. 24.

![Fig.24 Discrimination scores for /ba/ and /ab/. See table 6, appendix, for significance levels.](image)
The d' values are now larger than those for /da/ and /ad/ but the results show the same tendency that was observed for /da/ and /ad/. The discrimination among VC syllables was better than among their mirror image CVs. The difference between the VC and CV discrimination scores was very significant (p<.01) for dF2=150Hz and dF2=250Hz, significant (p<.05) for dF2=300Hz and non-significant for the other F2 differences. A significance analysis of the differences between the present scores and those from the /da/ experiment (ch. 3.3) reveals that there are no significant differences between /da/ and /ba/, while some significant differences were found between /ad/ and /ab/, (see appendix with significance analysis).

6.4. Discussion

This experiment demonstrates that the increased discrimination among VC OFFPs is not related to a particular formant trajectory. Since in this case the F2 transitions are the opposite of those of the /da/ and /ad/ stimuli, the possibility that increased VC discrimination might be related to upwards F2 transitions must be rejected. Rather there is further support for the residual masking hypothesis.

The comparison of the /ba/ discrimination scores with those that had been obtained for /da/ reveals immediately that the discrimination performance for /ba/ was better than that observed for /da/. This difference in the performances needs to be examined more closely.

Considering that discrimination is reported in terms of d' values, the scores that were obtained for both /d/ and /b/ directly represent the perceptual differences between the reference stimulus of a series and each one of the other six stimuli of that series. By computing d' values instead of percentages of correct discriminations one automatically compensates for the effects of false-alarms and therefore a more stable measure of the perceived differences is obtained. However, in the case of the /b/ experiment, it is possible that the d' values have been affected by the particular sample of subjects used in the test. The four subjects that participated in the last experiment may not be typical listeners in the sense that they might have been unusually accurate in performing the task of discriminating among the /b/ stimuli.

The increased discrimination among VC syllables relative to their CV mirror images is a very persistent phenomenon, though incompatible with data from labeling experiments (Krull, 1983; Sidwell and Summerfield, 1986).
7. CAN A BURST IMPROVE STABILITY OF CV SYLLABLES?

7.1. Introduction

It has been argued that the characteristics of the onset spectra of stop-consonants may account for the perceptual invariance of CV utterances. The problem has been addressed both from a formal linguistic point of view (Blumstein and Stevens, 1979, 1980) and from an auditory perspective (Kewley-Port, 1983; Kewley-Port, Pisoni and Studdert-Kennedy, 1983; Kewley-Port and Luce, 1984). In particular, the work with auditory models shows the possibility of relating the spectral characteristics of the onset of CV utterances with relevant phonetic distinctions (Blomberg, Carlson, Elenius and Granström, 1986; Carlson and Granström, 1982; Delgutte, 1982, 1986; Klatt, 1982). Although these studies aim at finding auditory correlates of phonetic classes, they are related to the question of within class discrimination addressed in this thesis. Obviously, discrimination must underlay the capacity of classifying sounds in different phonetic categories, although the reverse may not be true (26). Therefore, this chapter addresses the problem of the role that stop-consonant release bursts might have in defining CV utterances in the light of the sensory smearing hypothesis.

7.2. Method

7.2.1. Stimuli

The stimuli were similar to the /da/ utterances from ch. 3, but this time they were synthesized with release bursts. The bursts were obtained by exciting the formant filters with a single excitation pulse before the onset of the transitions. The stimuli were organized in two series of seven utterances. In one of the series the burst was inserted 16ms before the onset of the transitions. In the other the time interval between the burst and the onset of the transitions was 33ms. The formant transitions were exponential and achieved 90% of their total range within the 50ms duration of the stimuli. The slope of the transitions was maximal at the locus. The formant values for the vowel target were F₁=750Hz, F₂=1250Hz, F₃=2400Hz and F₄=3050Hz. The

ONFPs of the reference stimulus was defined by \( F_1 = 200 \text{Hz}, F_2 = 1450 \text{Hz}, F_3 = 2600 \text{Hz} \) and \( F_4 = 3600 \text{Hz} \). The remaining six stimuli of each series were generated by increasing \( F_2 \) at ONFPs between 1600Hz and 1850Hz in steps of 50Hz. The voice source excitation had a constant \( F_0 = 120 \text{Hz} \). Open phase simulation was included in the same way as for the original /da/ stimuli.

7.2.2. Procedure

The perception test followed a non-adaptive, 2AFC paradigm, without feedback. The stimuli were presented in (A,X) and (X,A) pairs, where A is the reference stimulus and X another stimulus drawn from the same series. Each pair contained, therefore, either two /da/ stimuli with 16ms silent gap or two /da/ stimuli with 33ms silent gap. The time interval between the two elements in a pair was 350ms. The pause between consecutive pairs was 3.5s. After each group of 14 stimuli an extra 10s break was included. The stimuli were presented on-line from the computer. The subjects listened to the stimuli, in an anechoic room, via calibrated Sennheiser HD414 headphones. The test sessions were carried out with only one subject at a time.

7.2.3. Subjects

Six subjects participated in this experiment. They were adults with normal hearing and they had already been involved in other experiments reported here.
7.3. Results

The results are plotted in fig. 25. Note that the abscissas start at a higher dF2 value than that used in previous plots.

![Figure 25](image)

Fig. 25  Effect of a prefix burst on the discrimination among /da/ stimuli. See table 7, appendix, for significance levels.

This experiment shows that the discrimination of /da/ stimuli having a burst located 16ms before the CV ONFPs is roughly the same that is observed when the burst is located 33ms before the CV ONFPs. There is a slight tendency for the discrimination among the stimuli with 16ms gap to be somewhat better than when the gap is 33ms but this difference is significant only for dF2=350Hz (p<.05). The d’ scores were higher for this experiment than for the one investigating discriminations among /da/ without burst (ch. 3 and 4). A direct comparison of these results with those from the 16ms prefix /da/, shows no significant differences. However, the scores from the 33ms burst were significantly better than those from the 33ms prefix, for dF2 above 350Hz. See appendix with significance analysis.
7.4. Discussion

When compared to the results that were obtained with the "prefixed" ONFPs, the present discrimination scores are quite surprising. According to the sensory smearing hypothesis, discrimination should improve if the onset effect is allowed to generate sharp auditory representations of the CV ONFPs. That was, in fact, the outcome of the earlier experiment, in which the ONFPs were preceded by prefixes with constant F-patterns, equal to the ONFPs themselves. In this new experiment a further increase in discriminability among CV utterances is observed. What is surprising is that the effect is much stronger in the case of a burst before the CV ONFPs than when the ONFPs were preceded by the periodically excited prefixes.

Comparing the results of the experiment in ch.4.2 with the present results, shows that the latter are about 1 d' unit above the discrimination scores that had been observed for a 16ms prefix. In terms of the events occurring before the onset of the formant transitions, the 16ms prefix situation differs from the 16 ms burst by only one pulse and the question is whether this can account for the difference in the discrimination performance (27).

Because of the onset effect, a single burst could be expected to produce optimal sharpness of the auditory representation. In addition, if the auditory system's time window is of the order of 16ms, the discrimination performance for 16ms bursts may be slightly better than for a 33ms burst as a mere consequence of the energy summation under the time window. The major question here is whether the present results can be compared with previous experiments, since the group of subjects that was used in this experiment may not be representative. Otherwise, the present discrimination results do, in fact, support the expectations that were developed during the analysis and discussion of the earlier experiments. In particular, the fact that significant differences observed only between the 33ms burst and prefix conditions gives support to the sensory smearing hypothesis and the idea of an integration time of about 16ms.

27. The fact that the formant transitions used in the experiment of ch.4.2 were linear while the present ones were exponential can probably be disregarded in this context. If a comparison between situations where the stimuli have the same type of formant transition is required, then the results of the first /da/-/ad/ experiment can be used.

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8. DOES VC DISCRIMINABILITY DECREASE IN VCV UTTERANCES?

8.1. Introduction

The paradox between the VC discrimination results obtained in the previously reported experiments and VC discrimination generally observed for natural utterances (Pols and Schouten, 1978; Krull, 1983) was explained in psychoacoustic terms. To account for the fact that in natural speech the variability of the VC OFFPs is much higher than that of CV ONFPs (Lindblom and Lacerda, 1985, 1987) it was further suggested that the broader bandwidth of the formants at the VC OFFP, along with the overall decrease in intensity associated with the lowering of F1 could account for this paradox.

If discrimination among (synthetic) VC utterances is anchored in general psychoacoustic phenomena, why do languages seem to not exploit it? One possible answer is that the VC discriminatory advantage is only of marginal importance for a global optimization strategy. Another possibility is that this advantage vanishes when VC utterances are concatenated in VCV sequences.

The experiment described in this chapter was designed to study whether the greater ease of VC discrimination disappears in VCV utterances.

8.2. Method

8.2.1. Stimuli

The /ada/ stimuli for this experiment were obtained from two series of /da/ and /ad/ stimuli similar to those of ch. 3.2.1.

One series of seven /ad/ and another of seven /da/ components were created. The /a/ vowel had F1=750Hz, F2=1250Hz, F3=2400Hz and F4=3050Hz. The ONFPs and the OFFPs were described by F1=200Hz, F3=2600Hz and F4=3600Hz, while F2 varied from 1250Hz up to 1850Hz in equal 100Hz increments (28), to generate the

28. A pilot experiment was run using the stimuli of the /da/-/ad/ discrimination experiment but the discriminability of the resulting /ada/ stimuli was too poor. The dF2 step was, therefore, doubled.
seven /ad/ and the seven /da/ stimuli. The formant transitions between the vowel and the ONFPs or OFFPs were exponential, having their maximum slopes at the CV and VC boundaries. The duration of these VC and CV syllables was always 50ms. From these VC and CV components 14 VCV stimuli were obtained.

To create one series of /ada/ stimuli, each of the seven /da/ components was appended to the first element of the /ad/ series (F2=1250Hz), after a 70ms silent interval. This created a series of seven /ada/ stimuli, having a 70ms stop-consonant closure. The elements of this series differ from each other only in their F2 at CV OFFPs. This will be referred to as "ONFPs series". The other /ada/ series, the "OFFPs series", was generated by appending to each of the /ad/ components, the first element of the /da/ series, also after a 70ms silent interval. With this construction the reference elements of both /ada/ series are symmetrical (dF2=1250Hz) and equal to each other.

8.2.2. Procedure

The experiment was conducted using a non-adaptive 2AFC paradigm. No feedback was provided to the subjects during the test session. The /ada/ stimuli were presented in (A,X) and (X,A) pairs, where A is the first element of a series and X any element of that series. With this design, the utterances in each pair could only differ in terms of either the F2 value at the VC border or at the F2 at the CV boundary. In addition some control pairs were included in which there was no difference between the two utterances in the pair. The stimuli in each pair were separated by a 500ms pause. Between consecutive pairs there was a 3s interval, for the subjects to make their judgments. After the presentation of 14 pairs there was a pause of 10s. Each (A,X) and (X,A) pair was presented 5 times.

The subjects were asked to try to discriminate between the stimuli in each pair. No specific instructions were given, regarding what to listen to or how to listen.

The subjects listened to the stimuli via calibrated Sennheiser HD414 headphones, in an anechoic room. One or two subjects participated simultaneously in the experiment. The stimuli were presented on-line from the computer, using the set-up described above.
8.2.3. Subjects

Seven subjects participated in this discrimination test. Five of them were trained phoneticians while the other two were members of the laboratory staff. None of the subjects had reported or detected speech or hearing impairments.

8.3. Results

The discrimination scores are presented in fig. 26. The plot shows the evolution of the d' measure as a function of the distance dF2 between the F2 value of the ONFP or OFFP of the reference stimulus and that of the other stimulus in the pair.

Fig. 26  CV and VC locus discrimination in a VCV context, /ada/. See table 8, appendix, for significance levels.

The results show a small advantage of the discrimination among utterances differing in their VC OFFPs. The VC advantage is significant (p<.05) only for dF2=300Hz. See appendix with significance analysis.
8.4. Discussion

The data from this experiment show that the subjects discriminated more easily among stimuli differing in their VC OFFPs than when the same difference was present at the CV ONFPs. This is puzzling, particularly, in view of the discrimination data available from Sidwell and Summerfield’s (1986) experiment. It may, of course, be argued that the tasks involved in their experiment and in those reported here are different. While, they were interested in discrimination across phoneme boundaries, this and the other experiments have addressed within-category discrimination.

Another possible reason for the differences in the results might be related to the type of excitation source involved. In fact, the onset effect observed for the brief, constant F-pattern stimuli with noise source was much smaller than in the case of the periodic source. Furthermore, the discrimination results from those noise stimuli clustered at a discrimination corresponding to the non-adapted responses, suggesting that the noise-excited stimuli with gradual onsets produced less adaptation than the corresponding gradual onset stimuli with voice excitation did.

If it is true that noise excitation produces less ANF adaptation than periodic excitation, it may be that CV ONFPs are more easily discriminated than VC OFFPs because the residual masking produced by the VC OFFPs decreases as adaptation decreases, at the same time that the sensory smearing at CV ONFPs is probably not much affected.

An important aspect of the present results is that the differences in the discrimination among VC and CV ONFPs have decreased appreciably. Thus, the only statistically significant difference was observed for dF2=300Hz. In contrast differences obtained in the experiment of ch.3, were significant (p<.01) for dF2 above 100Hz. This is a clear indication that the VC advantage tends to vanish in VCV sequences.

The possible reason for the better discrimination results for the VC OFFPs may be that auditory pattern based on residual masking produced by the OFFP can be successfully processed during the 70ms long stop-gap. It seems reasonable that the discriminatory advantage of the VC OFFPs might be reduced if a shorter stop-gap was used. When compared with the durations observed in spontaneous speech, a 70ms gap is certainly on the upper limit of the normal ranges (Lindgren, Krull and Engstrand, 1987).

In summary, then, the paradox of the CV and VC discrimination results was not unambiguously explained by this experiment. This question will have to be further examined in future experiments.
9. FURTHER DEVELOPMENT OF THE SENSORY SMEARING HYPOTHESIS

Background for chapters 10 and 11

The sensory smearing hypothesis, as discussed in sections 3.4 and 4.2, states that auditory representation of the ONFPs of CV utterances may be blurred in case of rapid CV formant transitions. Along with the hypothesis of residual excitation, the sensory smearing hypothesis was used to explain the fact that discrimination among the synthetic VC utterances used in the experiments was significantly better than among matching CV utterances. The residual excitation hypothesis was tested by the "suffix" experiment of ch. 4.1 and further evaluated with the VCV utterances used in ch. 8. The results achieved in those experiments seem compatible with the residual excitation explanation. Also, the discrimination results for the different kinds of /da/ stimuli provide support for the sensory smearing hypothesis.

The sensory smearing hypothesis leads to interesting consequences in relation to categorical perception of the place of articulation for CV utterances. It is the purpose of the experiments in ch. 10 and 11 to evaluate those consequences. As a background, let us recall the main points related to the sensory smearing hypothesis:

(i) The discrimination scores among stimuli with $dF_2>150\text{Hz}$ and 16ms prefixes were significantly better than for the matching /da/ pairs of the experiment in ch. 3;

(ii) increasing the prefix duration from 16ms to 25ms or to 33ms did not result in improved discrimination relative to the original /da/ scores of ch. 3 (except for $dF_2=300\text{Hz}$ and 33ms prefix); and

(iii) the improvement achieved by the burst versions in relation to the original /da/ (ch. 7) was only significant for $dF_2=300\text{Hz}$.

In summary, a 16ms stationary ONFP, significantly improves discriminability among CV utterances. A possible consequence of this effect is that certain discrimination maxima in a continuum of CV place of articulation can be explained on an auditory rather than a phonemic basis. Specifically, it should be possible to demonstrate a dissociation between the locations of the discrimination peak and the phoneme boundary in a CV continuum of place of articulation, if adequate speech stimuli can be found.
One solution is suggested by the "locus equations" displayed in fig. 27 (Lindblom and Lacerda, 1985). The solid lines associated with /b/ and /d/ show how the F2 onset values relate to the corresponding target values. Each straight line corresponds to a stop consonant, and its slope can be interpreted as an anticipatory coarticulation factor. The dashed diagonal indicates the CV utterances having equal F2 at onset and target. In particular, this dashed line represents the CV utterances that would be best discriminated if the sensory smearing hypothesis is true. It is an important consequence of this hypothesis that the location of the discrimination maximum for the /ba/-/da/ continuum is at about the F2 value predicted by categorical perception considerations. In contrast, for /bi/-/di/ or /bu/-/du/ continua, the discrimination maxima predictions based on of the sensory smearing hypothesis differ from those based on categorical perception. It is the purpose of the next two experiments to evaluate this line of reasoning.

Fig. 27 "Locus equations" for F2. Data from Linblom and Lacerda, 1986.
10. DISCRIMINATION OF /Cu/ UTTERANCES

10.1 Introduction

Two related experiments - a discrimination and an identification experiment - will be reported in this chapter. Together, they attempt to dissociate identification from discrimination of speech sounds. The idea that the observed discrimination peak located at the phoneme boundary is associated with identification of phonemes on either side of the boundary is questioned here. An alternative account based on the sensory smearing hypothesis is presented and tested.

It was assumed in ch. 9.0 that the typical discrimination peak observed between /ba/ and /da/ might be related to the occurrence of maximally flat F2 transitions, leading to optimal auditory representations of the CV onset patterns in that region. Unfortunately, for this continuum the F2 value for the discrimination peak and the F2 value for the phoneme boundary are about the same. It is therefore impossible to decide whether the discrimination peak can be accounted for mainly on auditory or on phonemic grounds. On the other hand, the respective hypothesis of sensory smearing and categorical perception do predict different outcomes for the /bi/-/di/ and the /bu/-/du/ continua. The problem now is to synthesize good enough representatives of these continua by varying only the onset frequency of F2.

This constraint immediately rules out the possibility of using /Ci/ utterances. The fact that all the /b/ and /d/ lines in fig. 27 converge for high F2 values indicates that /bi/-/di/ differences cannot be obtained by F2 alone. The alternative possibility, /Cu/, is more promising. To be sure, F3 at CV onset is not the same for /bu/ and /du/, but a compromise F3 value was found by trial and error. For this continuum, the sensory smearing hypothesis predicts a discrimination peak at a lower F2 value than that corresponding to the phoneme boundary.

The present experiments are intended to be comparable with other experimental investigations of categorical perception of place of articulation. However, there are some design differences. At this point, my strategy was to keep the format and type of stimuli as close as possible to that of the above F2 discrimination experiments so that the new discrimination results could be directly related to the sensory smearing hypothesis. This solution involves, at least, the following differences between these and other similar experiments:

The discrimination and identification experiments carried out by Liberman et al. (1957), Mattingly, Liberman, Syrdal and Halwes, (1971) and Kuhl and Padden (1983) used two-formant stimuli. In contrast, the experiments described above were carried out with four-formant stimuli. Also, the duration of their stimuli was about five times greater than that of the present ones. Finally, the F2 interval difference between the stimuli in the pairs was also different.

It should be noticed in addition that Liberman et al.'s (1957) discrimination experiment was carried out after the subjects first having identified the stimuli as
speech sounds. The fact that identification preceded discrimination probably introduced some bias in the experiment. However, this does not seem to have influenced the general picture substantially since later experiments, carried out in reverse order, have corroborated Liberman et al.'s finding that discrimination increases across phoneme boundary for the /Ca/ continuum.

10.2. Method

10.2.1. Stimuli

The stimuli for this experiment were generated by the same procedures as were used for the /ba/ and /da/ stimuli described in earlier experiments. The optimal range of F2 onset values and the F3 value at onset were adjusted, by trial and error, in several pilot test runs with the experimenter as a subject.

The transitions were exponential, with their maximum slope at CV onset. They achieved 90% of the total transition range under the 50ms duration of the stimuli. The formant values for the target vowel were set at F1=300Hz, F2=700Hz, F3=2560 and F4=3300Hz. The ONFPs were defined by F1=200Hz, F2=600Hz, F3=2000Hz and F4=3300Hz. The F2 value in the ONFPs was increased in constant 50Hz steps from 600Hz up to 1750Hz. The resulting 24 stimuli covered the whole range from /bu/ to /du/ (see fig. 27). The fundamental frequency was constant and equal to 120Hz for all the stimuli.

10.2.2. Procedure

To replicate earlier categorical perception experiments (e.g. Liberman et al., 1957), two related experiments must be performed with these stimuli, one for discrimination and one for identification.

The stimuli for the discrimination experiment were organized into a constant step discrimination paradigm. The utterances were presented in pairs that consisted of one stimulus randomly drawn from the pool of 24 and another that had a F2 locus 200Hz above or below the first selected stimulus. A number of control pairs, formed by two identical stimuli, were included in the presentation to check the consistency of the subject’s responses. These control pairs were also randomly selected from the pool of available stimuli.
The stimuli in the pairs were separated by 350ms of silence. The time interval between consecutive pairs was 3s. After the presentation of 12 pairs there was a 10s pause to allow the subject to rest and to mark the end of a group.

Before the test proper, the subjects had a training session during which they could practice listening to all the pairs of stimuli that would be used in the test. The test proper consisted of 120 observations of stimuli pairs (organized in 10 groups of 12 pairs). The test session followed the training session, after a pause of 30s.

The subjects were instructed to listen to the two sounds of each pair and to judge their similarity by circling "S" or "D" (for Same or Different) in their answer form. No feedback was given to the subjects and they were requested to answer always, even though they might be not sure (2AFC). The instructions were written in English on the answer sheets. The word "sound" was intentionally used when referring to the stimuli to avoid biasing the subjects to process the stimuli as speech. Nevertheless, when commenting on the experiment, after the test sessions, most of the subjects referred to the stimuli as speech utterances.

The perception tests were always conducted in an anechoic room and, in most cases, with two subjects simultaneously. A record was kept of the subjects who performed the task simultaneously to permit a subsequent check of the test situation. Just as in the previous experiments, the subjects listened to the stimuli over Sennheiser HD414 headphones. The presentation level was the same for all the subjects within a 1dB error margin. Due to the large number of stimuli pairs involved in this experiment, the number of repetitions of each pair was reduced in order to keep the test reasonably short (about 12 minutes, including the training session). Each subject made only four observations for each particular pair.

Using the stimuli from the /bu/-/du/ continuum, an identification test was carried out. The subjects were asked to classify the utterances either as /bu/ or as /du/ in a 2AFC paradigm.

10.2.3. Subjects

The 13 subjects for the discrimination test were Swedish or English speaking adults without any reported hearing or speech problems. Their experience of this type of perception tests varied considerably (from very experienced to absolutely naive). Two of the subjects who had participated in the discrimination test (one naive subject and a trained subject) took also the identification test.
10.3. Results

Fig. 28 shows the discrimination scores for these /bu/-/du/ stimuli.

The abscissas show the F2 averages at the CV boundary for the paired stimuli. The values were computed in Hz and subsequently converted to Bark. The ordinates show the percentage of correct discriminations for each pair. The phoneme boundary was defined as the 50% point in the identification function and is indicated by the vertical line in the figure. The percentage of /bu/ identifications dropped from above 90% at 1.050kHz to 0% at 1.650kHz.

10.4. Discussion

Assuming that the phoneme boundary is represented by the stimulus producing 50% category assignments for each class, it is clear that the peak of discrimination is not at the phoneme boundary. That peak is located at a F2 value lower than the phoneme boundary, in the direction predicted by the sensory smearing hypothesis. However, these data do not provide unequivocal support for the sensory smearing hypothesis according to which the optimal F2 transition should occur for 700Hz (flat F2 transition). Such a mismatch between the predicted and the observed discrimination peak is not surprising since it is unlikely that a single component can account for the
effect. Before any further discussion, let us consider the outcome of the corresponding /Ca/ discrimination and identification experiment to be described in the next chapter. These CV stimuli have more complex F-patterns than the ones used by Liberman et al. (1957) or Kuhl and Padden (1983). It is reasonable to assume that this increased complexity will affect the discrimination response patterns. A general discussion of the /Cu/ and /Ca/ results will be made in ch. 12 ("ID-dissociation").

11. DISCRIMINATION OF /Ca/ UTTERANCES

11.1. Introduction

The experiment described in this section is structurally identical with the previous one. It is a discrimination and identification test run with a /ba/-/da/ stimulus continuum. As explained in ch. 9.0, the respective hypothesis postulating sensory smearing and categorical perception predict the same discrimination peak location for this continuum.

11.2. Method

11.2.1. Stimuli

The stimuli for this experiment are similar to those used in the previous one. The duration of the stimuli was 50ms. The transitions were exponential, with their highest slope at the CV onset and achieving 90% of their total excursion range within the 50ms duration of the stimuli. The vowel target for these stimuli was specified by F1=750Hz, F2=1259Hz, F3=2400Hz and F4=3050Hz. The onset formant values for the CV utterances were fixed F1=200Hz, F3=2600Hz and F4=3050Hz. The F2 values were varied from 606Hz (5.8Bark) up to 1772Hz (12.2Bark), in 16 equal steps of .4 Bark each. The Bark to frequency conversion was made using Traunmuller's (1983) expressions (cf. ch. 1.3.1). These stimuli cover the whole range from /ba/ to /da/. The constant step in Bark was introduced to obtain equal increments in the tonotopical representation of the F2 loci patterns.
11.2.2. Procedure

A discrimination perception test and an identification test were run for this set of stimuli. In the discrimination test the stimuli were presented in pairs differing by 1.6Bark at their F2 onset values. The order of the elements in the pairs was balanced, i.e. there were (X1,X2) and (X2,X1) pairs, where X2 represents a stimulus with higher F2 at onset than X1. To check the consistency of the responses, a few dummy pairs containing identical stimuli were included. These pairs were drawn at random from the pool of 17 available /Ca/ stimuli. The time interval between the stimuli in a pair was 350ms. There was an interval of 3s between consecutive pairs. An extra pause of 10s was inserted after a group of 12 pairs to mark its end.

The identification experiment was carried out by presenting the 17 stimuli in isolation and having the subjects decide whether the stimulus was /ba/ or /da/. The 2AFC paradigm, without feedback was used in both tests. In the discrimination task the subjects were asked to detect differences between the sounds in each pair. Therefore, to minimize the effects of treating the stimuli as speech sounds, the discrimination experiment was carried out first. The test was carried out in an anechoic room and the stimuli were delivered on-line, from pre-recorded computer files. The number of subjects per test session was either one or two. For a later study of the effects of single and double sessions on the results of the perception tests, information about the subjects and their particular test situation was recorded.

11.2.3. Subjects

The 5 subjects for these perception tests were adults, fluent speakers of Swedish and English. They had no reported or detected language or hearing problems. Most of the subjects were members of the staff of the laboratory of phonetics and part of them had participated in one or more of the experiments reported above.
11.3. Results

The results of the /Ca/ discrimination test are presented in fig. 29. The ordinate shows the percentage of correct discriminations for each pair. The pairs are represented by the average of the F2 onset values of their elements, expressed in Bark. The solid squares show the average discrimination scores obtained for five subjects. According to the identification results, the 50% phoneme boundary was located at the stimulus with F2=1229Hz (9.8Bark).

![Graph showing discrimination and labeling scores for /ba/-/da/.

To obtain a measure of the reliability of the results, the discrimination scores from the entire group of subjects were compared to those that would be obtained in case the performance of the group were at chance level. This was done by dividing the discrimination data in two frequency bands and applying Wilcoxon’s statistical test (Siegel, 1956, pp.75-83) (29). The null hypothesis is that the discrimination results for each band were generated by an uniform distribution, corresponding to a uniform 50% correct discrimination of each pair. One of the frequency bands was defined as being from 606Hz (5.8Bark) to 883Hz (7.8Bark) and the other from 946Hz (8.2Bark) to 1391Hz (10.6Bark). No significant difference was found between the discrimination scores produced by the stimuli in the 606Hz-883Hz band and those produced by

29. 70% correct discriminations is clearly better than 60% correct discriminations. However, the 10% interval between these scores may not be equivalent to the 10% interval between 20% and 30%. To avoid this problem, Wilcoxon’s test was used since it only requires an ordinal scale. This is a condition clearly met by the discrimination scores.
chance discrimination (30). On the other hand, the discrimination scores coming from the frequencies between 946Hz and 1391Hz were very significantly above chance level (p<.01).

11.4. Discussion

This experiment functions as a "calibration" of the discrimination and identification experiment that was reported in the previous chapter. Both the sensory smearing hypothesis and the classical categorical experiments predict that the discrimination peak of the /Ca/ continuum is coincident with the phoneme boundary.

The /b/-/d/ phoneme boundary for the /Ca/ utterances was located at the stimulus that had an onset F2 at 1229Hz. Incidentally, it corresponds to the maximally flat F2 transition, since the second formant of the /a/ vowel is defined at 1259Hz.

The results corroborate the expectations that the discrimination peak is located close to the phoneme boundary. However, the discrimination peak is spread down to about 1.2Bark below the phoneme boundary but the important aspect of this experiment is not the absolute location of the phoneme boundary. Since this experiment is a "calibration" of the alignment between the phoneme boundary and the discrimination peak, their actual locations are of secondary importance. Instead, it is the relative location of the discrimination peak and the phoneme boundary for the /Cu/ and /Ca/ continua that is relevant for the evaluation of the sensory smearing hypothesis. In particular, if the discrimination peak is related to the stability of the auditory representation of the ONFP of the CV utterances, one should be able to observe a dissociation between Identification and Discrimination ("ID-dissociation") for a continuum like /bu/-/du/.

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30. This non-significant difference results from the symmetry of the discrimination scores around the 50% level in this frequency region. The ranking order of the positive differences is about the same as that of the negative ones and, therefore, Wilcoxon's test cannot show any significant differences.
12. ID-DISSOCIATION

12.1. Introduction

To investigate the plausibility of an auditory account for some categorical effects in the perception of place of articulation, the ID-dissociation hypothesis is studied in this chapter, using the data from the two last experiments.

The sensory smearing hypothesis predicts a discrimination peak for stimuli pairs that generate stable auditory representations of their ONFPs. In particular it predicts that the /Cu/ and /Ca/ continua of ch. 10 and 11, that were generated by varying F2 at the ONFPs, will have maxima when stimuli of relatively flat F2 transitions are compared with each other. As a consequence, the discrimination peak for the /bu/-/du/ continuum should occur at a F2 frequency below that of the /b/-/d/ phoneme boundary, whereas for the /ba/-/da/ continuum the discrimination peak and the phoneme boundary should coincide.

12.2. Procedure

The differences in the structure of the discrimination data from /Cu/ and /Ca/ stimuli was evaluated in two ways:

One of the evaluations was made dividing the F2 range into two regions - one from 600Hz to 900Hz and the other above 900Hz - and comparing discrimination data from one test with matching data from the other. The matching pairs of data were constructed with stimuli for which the initial F2 values fell within a 25Hz interval of each other. The significance was tested by the Wilcoxon's test.

Another evaluation of the significance of the differences was made using the t-test. With the t-test (related) the significance of the differences in the evolution of the discrimination scores for /Cu/ was tested. The same procedure was applied to the /Ca/ continuum. Using a t-test (unrelated), the differences between corresponding scores from /Cu/ and /Ca/ were studied.
12.3. Results

The comparison of the discrimination performances between /Cu/ and /Ca/, using the Wilcoxon's test, showed significant differences (p<.05) for F2 values above 900Hz. The significance analysis within /Cu/ discriminations and within /Ca/ discriminations showed that the discrimination peaks were significant in both cases (see tables 9 and 10). Furthermore, the comparative analysis of /Cu/ and /Ca/ results indicates that discrimination near the respective phoneme boundaries was significantly different (table 11).

12.4. Discussion

The relative locations of the discrimination peaks and the phoneme boundaries obtained for /Cu/ and /Ca/ are different. The fact that the discrimination peak for the /Cu/ continuum is about 1 Bark lower than for /Ca/ and yet the /b/-/d/ phonemic boundary is approximately the same for /Cu/ and /Ca/, is an indication that the sensory smearing can play some role in the representation of these CV syllables. In other words, the comparison of the results from the /Cu/ and /Ca/ experiments illustrates the ID-dissociation effect and gives support to the idea that speech perception can be mediated by auditory representations of acoustic stimuli.

The observation of this ID-dissociation effect has direct theoretical implications for the notion that speech perception occurs in a special mode that does not build upon auditory representations of the speech sounds.
13. SUMMARY

This study is an attempt to exploit some available neurophysiological knowledge to generate and test predictions bearing on the discrimination of speech sounds. The concept of discharge rate adaptation has been basic to this endeavor. At the level of the auditory-nerve fiber (ANF), it means that the rate at which the fiber is able to discharge, i.e. to transmit neural action potentials, decreases as a function of the duration and intensity of the incoming stimulus. The dynamic range of the ANF will decrease correspondingly and, in consequence, the auditory representation of the signal will undergo a certain amount of degradation.

The first experiment (ch. 2) investigated the auditory discrimination of synthetic stimuli of short duration and steady-state F- patterns. The stimuli started either abruptly or gradually. The set of stimuli within each such category was generated by varying the frequency of the second formant (F2) thus giving each stimulus an individual timbre. A listening test showed that the abrupt stimuli were better discriminated than the corresponding gradual stimuli. This result was interpreted in terms of the adaptation effect. Thus, it was assumed for the gradually starting stimuli that the ANF discharge rate had decreased before the stimulus was fully developed. In this study then, signals having a gradual onset were referred to as "the adapted stimuli".

For the abruptly starting signals, on the other hand, the ANF discharge rate was supposed to be at its maximum at onset. A correspondingly wide dynamic response range thus facilitated a relatively sharp auditory representation of the spectral pattern at that point. These signals were referred to as "the non-adapted stimuli" in the present experiments.

The significance of this first result thus lies in the possibility of relating general properties of auditory physiology to highly specific features of the perceptual processing of speech-like signals. In particular, the discrimination data obtained in the experiment strongly suggest that observed ANF adaptation patterns may play a role in enhancing crucial acoustic events in the speech signal. It seems as if the functional design of the inner ear is for some reason specialized for representing abrupt acoustic events particularly distinctly.

Another experiment (Ch. 5) was similar in design to the first one except that it used a noise source rather than a periodic voice source. This experiment, however, did not demonstrate a discriminatory advantage of the abrupt onset feature. Instead, discrimination between stimuli with gradual onsets was at the level of the discrimination between abrupt onset stimuli. The reason for this is not completely clear. However, one possible explanation is based on the topological organization of the inner ear, as suggested in section 5.4.

Another experiment, reported in Ch. 3, was designed to further corroborate the discriminatory advantage of stimuli giving rise to non-adapted auditory responses. This experiment used a periodic voice-like source. The point of departure was the assumption that onset spectra (ONFP), pertaining to abruptly starting CV stimuli, would produce non-adapted responses and therefore be more reliably discriminated.
than the offset spectra (OFFP) of reversed VC stimuli, which are presented to ANF adapted by the initial vowel. The experiment thus called for a set of more speech-like stimuli. Therefore, time-variation was introduced in the F-pattern. The experimental variable was the onset and offset frequency of F2.

There were two major results. First, the time-varying F-patterns led to a significantly lower discrimination rate as compared with the steady-state F-pattern stimuli of the first experiment. Second and unexpectedly, the VC stimuli turned out to be better discriminated than the CV stimuli.

The specific purpose of the experiment reported in Ch. 6, was to examine the possibility that the discriminatory advantage of VC over CV as observed for the /da/-/ad/ stimuli was related to the F2 transition for these particular stimuli. Other studies (Lacerda and Moreira, 1982; Pols and Schouten, 1982, 1987) have suggested that the direction of the transition may affect the discrimination of synthetic stimuli. This effect would then be expected to show up for the syllables /ba/ and /ab/ where the F2 transitions are opposite to those of /da/ and /ad/.

However, this experiment produced a significant VC advantage also. In other words, the initial prediction was not substantiated. This finding is apparently incompatible with the data by Krull (1983) who observed lower discrimination scores for VC than for CV stimuli in natural speech. However, natural speech data are not completely comparable with the synthetic stimuli used in these experiments. In particular, segment boundary criteria for natural VC sequences are more difficult to define than the corresponding criteria for CV sequences. The reasons are, among others, increased F-bandwidths and changes in the source occurring at natural VC boundaries.

Of particular interest though was the finding that 16 ms prefixes of the CV onset F-pattern produced significant increases in the CV discrimination (ch. 4.2). The possibility of significantly change discrimination performance of "within phoneme boundary stimuli" - all /da/ utterances - has interesting theoretical implications as it offers a ground for an auditory account of the categorical perception of place of articulation in CV utterances. The explanation for the improvement in the CV discrimination when a short duration constant F-pattern preceded the onset of the CV transitions was that the sensory smearing of the CV onset spectral information was reduced.

This sensory smearing hypothesis came to be central to the experiments of this monograph. Once it was observed that discriminability among CV syllables increased by reducing the sensory smearing of the ONFP information, the next step was to study the possibility of accounting for categorical perception effects in the discrimination of stop consonant place of articulation.

The results of the categorical perception experiments for /Cu/ and /Ca/ (ch. 10 and 11) revealed a form of dissociation between the boundary for phoneme identification and the discrimination peak (ID-dissociation effect). The discrimination peak is not exactly located at the F2 value producing a flat formant transition, as predicted by the sensory smearing hypothesis but it is, nevertheless, significantly displaced from the phoneme boundary, in that direction (ch. 12). Since the stimuli were generated by a series synthesizer, the displacement of the discrimination peak for /Cu/ may be due to the variation in the second formant level that is produced by the first formant transition. This aspect was not investigated. The displacement of the /Cu/ discrimination peak in relation to the /b/-/d/ phoneme boundary is interesting from a theoretical point of view, as it points to an auditory basis for categorical perception effects in the discrimination of place of articulation of CV syllables.
14. THEORETICAL IMPLICATIONS

14.1. Introduction

What relevance do the perception experiments reported in this monograph have for the understanding of the speech communication process?

In immediate practical terms, the consequences of the advantage in the discrimination of sounds with abrupt onsets of stimulation may be very limited. As stated before, everyday speech communication cannot be critically dependent on auditory effects that are as subtle as those that were studied here. However, the onset effect and sensory smearing may play a role in the organization of languages in general. A look at the phoneme inventories of languages of the world (Maddieson, 1984) reveals that while 53.9% of the languages use 3 stop consonants, the most frequent number of fricatives, two, occurs only in 19.6% of the languages. This is a clear advantage of the sounds that can take advantage of the onset effect. Furthermore, vowels are also sounds with abrupt onsets.

That "within phoneme class" discrimination of CV utterances is poorer than "across class" discrimination is a commonly observed phenomenon. It has also been observed that these considerable differences in discrimination performance for CV syllables are not observed for comparisons among vowels. This leads to an account based on the persistence of the cues for place of articulation in the precategorical acoustic storage (PAS) (Crowder and Morton, 1969; Crowder, 1981). This view relates categorical perception effects of initial position stop consonants with rapidly vanishing auditory representations of the consonant onset patterns in the PAS (Pisoni, 1973; Crowder, 1982). No such prominent categorical effects are observed for vowels because they produce more stable representations. In short, categorical perception of stop consonants is associated with transient auditory representations that have to be rapidly classified as one of the relevant stop consonants, before they disappear from the PAS.

A possible explanation of the poor CV discrimination can be given on a purely auditory basis, taking into account that adaptation of the ANFs does not occur instantaneously: Since a few glottal pulses are delivered during the CV formant transition before adaptation has had time to develop fully, the locus auditory information provided by the first glottal pulse may be blurred by the immediately following "off tune" auditory patterns. For the VC utterances, it is the residual excitation produced by the final loci? that supports their discrimination.

A possible explanation for the poor CV discrimination can be given in purely auditory basis, taking into account that adaptation of the ANFs does not occur instantaneously: Since a few glottal pulses are delivered during the CV formant transition before adaptation has had time to develop fully, the locus auditory information provided by the first glottal pulse may be blurred by the immediately
following "off tune" auditory patterns. In what concerns the VC utterances, it is the residual excitation produced by the OFFPs that supports their discrimination.

The results of the discrimination experiment run with /da/ stimuli demonstrated a drastic reduction of the discriminability, as compared to that of the constant F-pattern stimuli. This outcome, by itself, is in line with the categorical perception of stop-consonant’s place of articulation. However, when this /da/ data is compared with the /ad/ data of the same experiment, new questions have to be asked. The fact that "mirror image" /ad/ utterances were significantly better discriminated than /da/ utterances, by the same subjects, puts difficulties to a straight forward categorical perception account, based on the PAS latency time of the locus cues. Incidentally, the outcome cannot be accounted either by a straight forward onset effect. On the other hand, the increased contrast of the auditory representations of rapid upward frequency sweeps could be offered as an explanation for the /ad/ advantage but this possibility is not compatible with the results of the /ba-/ab/ experiment. Here too, VC was better discriminated than CV and yet the /ba/ stimuli are the ones having upwards F2 transitions, for which the enhanced tracking contrast could assist discrimination.

The sensory smearing hypothesis became the main driving force for the experiments of this monograph. Once it was observed that discriminability among CV syllables increased by reducing the sensory smearing of the locus information, the next step was studying the possibility of accounting for categorical perception effects in the discrimination of stop-consonant place of articulation.

14.2. Categorical perception and the "speech mode"

Speech signals are continuous and variable. For a successful speech communication the auditory system must be able to disregard the linguistically irrelevant variability in the acoustic signal (Lindblom, 1986, "invariance" and "segmentation" issues, p.495). This is a task nicely performed by categorical perception: the system has leeway to allow for within category variations, but it is sensitive to variation that crosses over category boundaries.

Categorical perception was therefore an argument for a special perception mode for speech (Liberman, Cooper, Shankweiler and Studdert-Kennedy, 1967). While it was observed that the discrimination of continua of non-speech sounds was monotonically related to the physical difference between the sounds, the results were radically different when speech stimuli were used in similar discrimination tasks (Cutting and Rosner, 1974): stimuli that were identified as members of the same phoneme, were very poorly discriminated. In contrast, stimuli identified as belonging to different phoneme categories received much higher discrimination scores (Liberman et al., 1957).

This highly provocative approach initiated a number of investigations. One line of inquiry dealt with contextual effects such as boundary displacements associated with the extension (range) of the continuum and the previous exposure to samples (frequency) from one of the categories. This type of influence is usually referred to by range and frequency effects (Parducci, 1965; Rosen, 1979). It was also shown that the categorization of a continuum could be influenced by the context in which the stimuli
were presented (Repp, 1982). Another approach questions the interpretation of the
categorization results as support to categorical perception, itself (Hary and Massaro,
1982; Massaro, 1987).

While it is generally accepted that the perceptual system must be flexible enough
to cope with a considerable acoustic variability, the processes underlying such a
flexibility have been subject to different interpretations. In particular, these
interpretations differ in the extent to which they view categorical perception
processing as a consequence of the general functioning of the auditory system.
According to one view, speech perception is special in the sense that it cannot be
accounted for by general auditory mechanisms (Liberman and Mattingly, 1985;
Liberman, 1982; Liberman, Isenberg and Rakerd, 1981; Liberman and Studdert-
Kennedy, 1978). Furthermore, some workers have proposed the existence of specific
innate processing mechanisms which are automatically triggered when exposed to
speech (Eimas, 1974, 1975). Still others claim that speech perception has to rely on
general auditory mechanisms (Howell and Rosen, 1984; Kuhl, 1981, 1985, 1986; Kuhl
and Padden, 1983; Petersen and Jusczyk, 1984; Stevens, 1981).

Arguments in support of the notion of a specialized speech mode of perception
have been launched along different lines. For example, in the view of Liberman and
Studdert-Kennedy (1978), a purely auditory processing of speech sounds would not be
compatible with the special nature of the speech code. They view spoken utterances as
concatenations of a small set of basic building-blocks, the phonemes which, carrying
no semantic meaning in themselves, can be combined to form a large number of
meaningful entities such as words or morphemes ("double articulation", as it was
called by Martinet). The price paid for this highly efficient coding principle is that the
link between sound sequences and meaning is an arbitrary one (Saussure, 1916).
Apparently then, speech perception must involve an analysis of the phoneme
sequences that constitute words and sentences. However, the classical formulation of
the invariance issue tells us that there is no one-to-one relationship between phonemes
and observable speech sounds. The articulatory and acoustic characteristics of speech
sounds are commonly affected by factors such as coarticulation (Liberman et al., 1967)
and speech rate (Lindblom, 1963; Lindgren, Krull and Engstrand, 1987). A non-
specialized auditory processing strategy thus seems to involve a rather heavy load on
the perceptual system. It has been suggested, therefore, that the perception of speech
and non-speech sounds might involve "different, active 'attentional' modes of
scanning the signal for information" (Studdert-Kennedy, 1982, p.10).

Further arguments in support of the specialized speech mode have been advanced
in terms of the so-called "duplex perception" (Liberman and Studdert-Kennedy, 1978;
Studdert-Kennedy, 1982) and "trading relations" (Repp, 1982) among different speech
features. Finally, the intermodal experiments on speech perception (McGurk and
MacDonald, 1976; Summerfield, 1979; Roberts and Summerfield, 1981) suggest that
speech perception is not an exclusively auditory process, but rather an integrated,
intermodal one. The better point, of course, is related to the particular theory of speech
perception known as the motor theory (Liberman and Mattingly, 1985; Liberman,
1982; Liberman, Isenberg and Rakerd, 1981). According to this model, the listener
uses the variable acoustic input to form an hypothesis as to its phonemic structure,
which is subsequently implemented by implicit articulation. A good match with the
incoming flow of speech then constitutes the criterion of a successful identification.

In my view, given the nature and function of the speech signal it is reasonable to
accept that speech might be treated in a special way. However, I take the idea that
specialized speech mechanisms might be innate (Eimas, 1974, 1975) as an over-
generalization of the findings that human infants show categorical perception effects at
a prelinguistic stage (Miller and Morse, 1976). Alternatively, their results may be taken to suggest that languages exploit general auditory sensitivities (Stevens, 1981) which may be the result of a phylogenetic evolutionary process (31).

In a phylogenetic perspective, it is reasonable to assume that the evolution of language has been accompanied by some form of specialization for various classes of ecologically important sound effects (Lindblom, MacNeilage and Studdert-Kennedy, 1988). The apparent innate specialization for speech sounds observed in infants would then reflect a more general capacity to discriminate among classes of sounds.

The possible significance of categorical perception in support of a specialized phonetic mode of speech perception must thus be examined in the light of experiments demonstrating categorization effects for non-speech continua, both for adult listeners (Miller, J., Wier, Pastore, Kelly and Dooling, 1976; Pisoni, 1977; Jusczyk, Pisoni, Walley; and Murphy, 1980) and infants (Howell et al., 1977; Jusczyk, Pisoni, Reed, Fernald and Myers, 1983). The fact that such effects have been observed in experiments with non-speech sounds suggests that general auditory processes might also be sufficient to explain the categorical perception of speech sounds.

14.3. Auditory basis for speech perception

As noted above, categorical perception effects have been observed for non-speech as well as speech sound continua. This fact strongly suggests that categorization is not associated with the perception of speech alone. On the other hand, the assumption that our capacity to process speech-like sounds may have evolved along with a phylogenetic optimization of general auditory sensitivities is strengthened by experimental data on infants (Howell, Rosner, Cutting, Foard and Smith, 1977; Kuhl, 1979; Bertoncini and Mehler, 1981; Aslin, Pisoni and Jusczyk, 1983; Johansson, 1983; Bertoncini, Bijeljac-Babic, Blumstein and Mehler, 1987). Although infants are able to discriminate among linguistically relevant acoustic dimensions of speech-like stimuli, this does not justify the conclusion that humans are endowed with an innate representation of phonological units. In particular, the similarity of human and non-human performance in these discrimination tasks supports the idea that the general auditory processes are basic to the categorization of the voiced-voiceless and place continua. In fact, discrimination studies of VOT have shown that both chinchillas (Kuhl and Miller, J., 1975) and macaques (Kuhl and Padden, 1982) display a discrimination pattern that is very similar to that observed for humans. Also non-human have been shown to display categorical perception of place of articulation of stop-consonant (Morse and Snowdon, 1975; Sinnot, Beecher, Moody and Stebbins, 1976; Kuhl and Padden, 1983). Those effects, too, parallel the ones observed in experiments with human subjects (32).

31. See Petersen and Jusczyk (1984) for an elaboration of this view.

32. Incidentally, there is not a perfect match between the placement of the phoneme boundaries observed in Kuhl and Padden's experiment and the predictions directly based on the sensory smearing hypothesis. A strict prediction of the sensory smearing hypothesis would be a /b/-/d/ boundary placed at their stimulus 7.
Another piece of evidence comes from the observations made by Seyfarth, Cheney and Marler (1980a,b) and by Snowdon, Brown and Petersen (1982) as quoted by Petersen and Jusczyk (1984): "...monkey vocalizations are like human speech sounds in the sense that any single utterance carries many pieces of information" (p.596). An important finding was that the monkeys achieved good discrimination performance more easily when the arbitrary stimuli included acoustic dimensions that were communicatively relevant (Petersen and Jusczyk, 1984:597). The stimuli seem to have provoked a general attentive mode of information processing.

The implication of these experiments is that human discriminatory performance in response to speech-like sound stimuli is not unique. In contrast, stimulus categorization may be a very general feature of the strategy for decoding complex acoustic signals containing vast amounts of information (Lindblom, MacNeilage and Studdert-Kennedy, 1984; Petersen and Jusczyk, 1984). In this thesis, one of the possible auditory grounds for categorization of CV utterances was investigated. Certainly, the role of ANF adaptation in speech communication is discreet, but permanent. By studying some consequences that the ANF adaptation seems to have for the discrimination between speech sounds, I hope to contribute for the discussion of speech processes in an evolutionary perspective.
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TABLE 1

FILE: brief.dl  
Brief, constant F-pattern stimuli, periodic source  
dF2=30Hz, Range: F2(0)=1510Hz, ..., F2(6)=1690Hz

Within series comparison (abrupt):  
one tailed t-test (related) at df=18  
Comparing 0 and 1: Significant at p <-0.0005  
Comparing 0 and 2: Significant at p <-0.0500  
Comparing 0 and 3: Non-significant difference  
Comparing 0 and 4: Non-significant difference  
Comparing 0 and 5: Non-significant difference  
Comparing 0 and 6: Significant at p < 0.1000  
Comparing 1 and 2: Significant at p < 0.0005  
Comparing 1 and 3: Significant at p < 0.0005  
Comparing 1 and 4: Significant at p < 0.0005  
Comparing 1 and 5: Significant at p < 0.0005  
Comparing 1 and 6: Significant at p < 0.0005  
Comparing 2 and 3: Significant at p < 0.0500  
Comparing 2 and 4: Significant at p < 0.0250  
Comparing 2 and 5: Significant at p < 0.0100  
Comparing 2 and 6: Significant at p < 0.0050  
Comparing 3 and 4: Non-significant difference  
Comparing 3 and 5: Non-significant difference  
Comparing 3 and 6: Significant at p < 0.1000  
Comparing 4 and 5: Non-significant difference  
Comparing 4 and 6: Significant at p < 0.0500  
Comparing 5 and 6: Significant at p < 0.1000

Inter series comparisons (abrupt versus gradual):  
Comparing 0 and 0: Non-significant difference  
Comparing 0 and 1: Significant at p <-0.0005  
Comparing 0 and 2: Significant at p <-0.0005  
Comparing 0 and 3: Significant at p <-0.0250  
Comparing 0 and 4: Non-significant difference  
Comparing 0 and 5: Non-significant difference  
Comparing 0 and 6: Non-significant difference  
Comparing 1 and 0: Significant at p < 0.0005  
Comparing 1 and 1: Significant at p <-0.0500  
Comparing 1 and 2: Significant at p < 0.0250  
Comparing 1 and 3: Significant at p < 0.0005  
Comparing 1 and 4: Significant at p < 0.0005  
Comparing 1 and 5: Significant at p < 0.0005  
Comparing 1 and 6: Significant at p < 0.0005  
Comparing 2 and 0: Significant at p < 0.1000  
Comparing 2 and 1: Significant at p <-0.0005  
Comparing 2 and 2: Significant at p <-0.0250  
Comparing 2 and 3: Non-significant difference  
Comparing 2 and 4: Non-significant difference  
Comparing 2 and 5: Significant at p < 0.0500  
Comparing 2 and 6: Significant at p < 0.0250
Comparing 3 and 0: Non-significant difference
Comparing 3 and 1: Significant at $p < 0.0005$
Comparing 3 and 2: Significant at $p < 0.0005$
Comparing 3 and 3: Significant at $p < 0.0500$
Comparing 3 and 4: Non-significant difference
Comparing 3 and 5: Non-significant difference
Comparing 3 and 6: Non-significant difference
Comparing 4 and 0: Non-significant difference
Comparing 4 and 1: Significant at $p < 0.0005$
Comparing 4 and 2: Significant at $p < 0.0005$
Comparing 4 and 3: Significant at $p < 0.0050$
Comparing 4 and 4: Significant at $p < 0.0005$
Comparing 4 and 5: Non-significant difference
Comparing 4 and 6: Non-significant difference
Comparing 5 and 0: Non-significant difference
Comparing 5 and 1: Significant at $p < 0.0005$
Comparing 5 and 2: Significant at $p < 0.0005$
Comparing 5 and 3: Significant at $p < 0.0500$
Comparing 5 and 4: Significant at $p < 0.0500$
Comparing 5 and 5: Non-significant difference
Comparing 5 and 6: Non-significant difference
Comparing 6 and 0: Non-significant difference
Comparing 6 and 1: Significant at $p < 0.0005$
Comparing 6 and 2: Significant at $p < 0.0005$
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Comparing 6 and 4: Significant at $p < 0.0500$
Comparing 6 and 5: Significant at $p < 0.0500$
Comparing 6 and 6: Non-significant difference

Within series comparisons (gradual):
Comparing 0 and 1: Significant at $p < 0.0005$
Comparing 0 and 2: Significant at $p < 0.0050$
Comparing 0 and 3: Significant at $p < 0.0500$
Comparing 0 and 4: Non-significant difference
Comparing 0 and 5: Non-significant difference
Comparing 0 and 6: Non-significant difference
Comparing 1 and 2: Significant at $p < 0.0005$
Comparing 1 and 3: Significant at $p < 0.0005$
Comparing 1 and 4: Significant at $p < 0.0005$
Comparing 1 and 5: Significant at $p < 0.0005$
Comparing 1 and 6: Significant at $p < 0.0005$
Comparing 2 and 3: Significant at $p < 0.0100$
Comparing 2 and 4: Significant at $p < 0.0005$
Comparing 2 and 5: Significant at $p < 0.0005$
Comparing 2 and 6: Significant at $p < 0.0005$
Comparing 3 and 4: Significant at $p < 0.0050$
Comparing 3 and 5: Significant at $p < 0.0005$
Comparing 3 and 6: Significant at $p < 0.0050$
Comparing 4 and 5: Significant at $p < 0.0500$
Comparing 4 and 6: Significant at $p < 0.0500$
Comparing 5 and 6: Non-significant difference
TABLE 2

FILE: daad.da /da/ and /ad/ stimuli (50ms)
dF2=50Hz, range: F2(0)=1450Hz,... F2(6)=1750Hz

Within series comparison (/da/):
one tailed t-test (related) at df= 14
Comparing 0 and 1: Significant at p <-0.0005
Comparing 0 and 2: Significant at p <-0.0005
Comparing 0 and 3: Significant at p <-0.0005
Comparing 0 and 4: Significant at p <-0.0005
Comparing 0 and 5: Significant at p <-0.0005
Comparing 0 and 6: Significant at p <-0.0050
Comparing 1 and 2: Non-significant difference
Comparing 1 and 3: Non-significant difference
Comparing 1 and 4: Non-significant difference
Comparing 1 and 5: Significant at p < 0.0005
Comparing 1 and 6: Significant at p < 0.0005
Comparing 2 and 3: Non-significant difference
Comparing 2 and 4: Significant at p < 0.1000
Comparing 2 and 5: Significant at p < 0.0250
Comparing 2 and 6: Significant at p < 0.0005
Comparing 3 and 4: Non-significant difference
Comparing 3 and 5: Non-significant difference
Comparing 3 and 6: Significant at p < 0.0050
Comparing 4 and 5: Non-significant difference
Comparing 4 and 6: Significant at p < 0.0050
Comparing 5 and 6: Significant at p < 0.0500

Inter series comparisons (/da/ versus /ad/):
Comparing 0 and 0: Significant at p <-0.1000
Comparing 0 and 1: Significant at p <-0.0005
Comparing 0 and 2: Significant at p <-0.0050
Comparing 0 and 3: Significant at p <-0.0005
Comparing 0 and 4: Significant at p <-0.0005
Comparing 0 and 5: Significant at p <-0.0100
Comparing 0 and 6: Non-significant difference
Comparing 1 and 0: Significant at p < 0.0005
Comparing 1 and 1: Non-significant difference
Comparing 1 and 2: Significant at p < 0.0050
Comparing 1 and 3: Significant at p < 0.0050
Comparing 1 and 4: Significant at p < 0.0050
Comparing 1 and 5: Significant at p < 0.0005
Comparing 1 and 6: Significant at p < 0.0005
Comparing 2 and 0: Significant at p < 0.0005
Comparing 2 and 1: Non-significant difference
Comparing 2 and 2: Significant at p < 0.0005
Comparing 2 and 3: Significant at p < 0.0050
Comparing 2 and 4: Significant at p < 0.0050
Comparing 2 and 5: Significant at p < 0.0005
Comparing 2 and 6: Significant at p < 0.0005
Comparing 3 and 0: Significant at p < 0.0005
Comparing 3 and 1: Non-significant difference
Comparing 3 and 2: Significant at p < 0.0100
Comparing 3 and 3: Significant at p < 0.0100
Comparing 3 and 4: Significant at p < 0.0250
Comparing 3 and 5: Significant at p < 0.0005
Comparing 3 and 6: Significant at p < 0.0005
Comparing 4 and 0: Significant at p < 0.0005
Comparing 4 and 1: Non-significant difference
Comparing 4 and 2: Significant at p < 0.0100
Comparing 4 and 3: Significant at p < 0.0250
Comparing 4 and 4: Significant at p < 0.0250
Comparing 4 and 5: Significant at p < 0.0005
Comparing 4 and 6: Significant at p < 0.0005
Comparing 5 and 0: Significant at p < 0.0005
Comparing 5 and 1: Non-significant difference
Comparing 5 and 2: Significant at p < 0.0500
Comparing 5 and 3: Significant at p < 0.1000
Comparing 5 and 4: Significant at p < 0.0500
Comparing 5 and 5: Significant at p < 0.0005
Comparing 5 and 6: Significant at p < 0.0005
Comparing 6 and 0: Significant at p < 0.0005
Comparing 6 and 1: Significant at p <= 0.0500
Comparing 6 and 2: Non-significant difference
Comparing 6 and 3: Non-significant difference
Comparing 6 and 4: Non-significant difference
Comparing 6 and 5: Significant at p < 0.0500
Comparing 6 and 6: Significant at p < 0.0005

Within series comparisons (/ad/):
Comparing 0 and 1: Significant at p <= 0.0050
Comparing 0 and 2: Significant at p <= 0.0500
Comparing 0 and 3: Significant at p <= 0.0250
Comparing 0 and 4: Significant at p <= 0.0500
Comparing 0 and 5: Significant at p <= 0.1000
Comparing 0 and 6: Non-significant difference
Comparing 1 and 2: Significant at p < 0.0050
Comparing 1 and 3: Significant at p < 0.0050
Comparing 1 and 4: Significant at p < 0.0005
Comparing 1 and 5: Significant at p < 0.0050
Comparing 1 and 6: Significant at p < 0.0005
Comparing 2 and 3: Non-significant difference
Comparing 2 and 4: Non-significant difference
Comparing 2 and 5: Significant at p < 0.1000
Comparing 2 and 6: Significant at p < 0.0050
Comparing 3 and 4: Non-significant difference
Comparing 3 and 5: Significant at p < 0.0500
Comparing 3 and 6: Significant at p < 0.0005
Comparing 4 and 5: Significant at p < 0.1000
Comparing 4 and 6: Significant at p < 0.0050
Comparing 5 and 6: Significant at p < 0.0050
**TABLE 3**

FILE: da16.da  Prefix /da/ stimuli

\(d\text{F}_2=100\text{Hz}, d\text{F}_2=50\text{Hz}\)  Range: \(F_2(0)=1450\text{Hz}, F_2(1)=1550\text{Hz}, \ldots F_2(6)=1800\text{Hz}\)

Within series comparison (16 ms pfx /da/):
one tailed t-test (related) at \(df=14\)

- Comparing 0 and 1: Significant at \(p<-0.0005\)
- Comparing 0 and 2: Significant at \(p<-0.0005\)
- Comparing 0 and 3: Significant at \(p<-0.0250\)
- Comparing 0 and 4: Non-significant difference
- Comparing 0 and 5: Significant at \(p<-0.0005\)
- Comparing 0 and 6: Significant at \(p<0.0500\)
- Comparing 1 and 2: Significant at \(p<0.1000\)
- Comparing 1 and 3: Significant at \(p<0.0005\)
- Comparing 1 and 4: Significant at \(p<0.0005\)
- Comparing 1 and 5: Significant at \(p<0.0005\)
- Comparing 1 and 6: Significant at \(p<0.0005\)
- Comparing 2 and 3: Significant at \(p<0.0005\)
- Comparing 2 and 4: Significant at \(p<0.0005\)
- Comparing 2 and 5: Significant at \(p<0.0005\)
- Comparing 2 and 6: Significant at \(p<0.0005\)
- Comparing 3 and 4: Significant at \(p<0.1000\)
- Comparing 3 and 5: Significant at \(p<0.0500\)
- Comparing 3 and 6: Significant at \(p<0.0050\)
- Comparing 4 and 5: Non-significant difference
- Comparing 4 and 6: Significant at \(p<0.0250\)
- Comparing 5 and 6: Significant at \(p<0.0005\)

Inter series comparisons (16 ms pfx /da/ versus 33 ms pfx /da/):

- Comparing 0 and 0: Significant at \(p<0.0100\)
- Comparing 0 and 1: Significant at \(p<-0.0005\)
- Comparing 0 and 2: Significant at \(p<-0.0005\)
- Comparing 0 and 3: Significant at \(p<-0.0005\)
- Comparing 0 and 4: Significant at \(p<-0.0005\)
- Comparing 0 and 5: Non-significant difference
- Comparing 0 and 6: Significant at \(p<-0.0500\)
- Comparing 1 and 0: Significant at \(p<0.0005\)
- Comparing 1 and 1: Significant at \(p<-0.0100\)
- Comparing 1 and 2: Non-significant difference
- Comparing 1 and 3: Non-significant difference
- Comparing 1 and 4: Non-significant difference
- Comparing 1 and 5: Significant at \(p<0.0005\)
- Comparing 1 and 6: Significant at \(p<0.0005\)
- Comparing 2 and 0: Significant at \(p<0.0005\)
- Comparing 2 and 1: Significant at \(p<-0.0005\)
- Comparing 2 and 2: Significant at \(p<-0.0500\)
- Comparing 2 and 3: Non-significant difference
- Comparing 2 and 4: Non-significant difference
- Comparing 2 and 5: Significant at \(p<0.0005\)
- Comparing 2 and 6: Significant at \(p<0.0050\)
Comparing 3 and 0: Significant at p < 0.0005
Comparing 3 and 1: Significant at p < 0.0005
Comparing 3 and 2: Significant at p < 0.0050
Comparing 3 and 3: Significant at p < 0.0005
Comparing 3 and 4: Significant at p < 0.0050
Comparing 3 and 5: Significant at p < 0.0005
Comparing 3 and 6: Non-significant difference
Comparing 4 and 0: Significant at p < 0.0100
Comparing 4 and 1: Significant at p < 0.0005
Comparing 4 and 2: Significant at p < 0.0050
Comparing 4 and 3: Significant at p < 0.0005
Comparing 4 and 4: Significant at p < 0.0005
Comparing 4 and 5: Non-significant difference
Comparing 4 and 6: Non-significant difference
Comparing 5 and 0: Significant at p < 0.0050
Comparing 5 and 1: Significant at p < 0.0005
Comparing 5 and 2: Significant at p < 0.0005
Comparing 5 and 3: Significant at p < 0.0005
Comparing 5 and 4: Significant at p < 0.0005
Comparing 5 and 5: Non-significant difference
Comparing 5 and 6: Non-significant difference
Comparing 6 and 0: Non-significant difference
Comparing 6 and 1: Significant at p < 0.0005
Comparing 6 and 2: Significant at p < 0.0005
Comparing 6 and 3: Significant at p < 0.0005
Comparing 6 and 4: Significant at p < 0.0005
Comparing 6 and 5: Significant at p < 0.0500
Comparing 6 and 6: Significant at p < 0.0100

Within series comparisons (33ms pfx /da/):
Comparing 0 and 1: Significant at p < 0.0005
Comparing 0 and 2: Significant at p < 0.0005
Comparing 0 and 3: Significant at p < 0.0005
Comparing 0 and 4: Significant at p < 0.0005
Comparing 0 and 5: Significant at p < 0.0250
Comparing 0 and 6: Significant at p < 0.0050
Comparing 1 and 2: Significant at p < 0.0100
Comparing 1 and 3: Significant at p < 0.0050
Comparing 1 and 4: Significant at p < 0.0050
Comparing 1 and 5: Significant at p < 0.0005
Comparing 1 and 6: Significant at p < 0.0005
Comparing 2 and 3: Non-significant difference
Comparing 2 and 4: Significant at p < 0.1000
Comparing 2 and 5: Significant at p < 0.0005
Comparing 2 and 6: Significant at p < 0.0050
Comparing 3 and 4: Non-significant difference
Comparing 3 and 5: Significant at p < 0.0005
Comparing 3 and 6: Significant at p < 0.0005
Comparing 4 and 5: Significant at p < 0.0050
Comparing 4 and 6: Significant at p < 0.0050
Comparing 5 and 6: Non-significant difference
TABLE 4

FILE:da25.da  Prefix ed /da/ and suffixed /ad/
            dF2=100Hz,dF2=50Hz Range: F2(0)=1450Hz, F2(1)=1550Hz,... F2(6)=1800Hz

Within series comparison (25ms pfx /da/):
    one tailed t-test (related) at df=12
    Comparing 0 and 1: Significant at p < -0.0005
    Comparing 0 and 2: Significant at p < -0.0005
    Comparing 0 and 3: Significant at p < -0.0005
    Comparing 0 and 4: Significant at p < -0.0005
    Comparing 0 and 5: Significant at p < -0.0005
    Comparing 0 and 6: Significant at p < -0.0005
    Comparing 1 and 2: Significant at p < 0.0100
    Comparing 1 and 3: Significant at p < 0.0250
    Comparing 1 and 4: Significant at p < 0.0250
    Comparing 1 and 5: Significant at p < 0.0250
    Comparing 1 and 6: Significant at p < 0.0250
    Comparing 2 and 3: Non-significant difference
    Comparing 2 and 4: Significant at p < 0.0500
    Comparing 2 and 5: Significant at p < 0.0050
    Comparing 2 and 6: Significant at p < 0.0050
    Comparing 3 and 4: Significant at p < 0.1000
    Comparing 3 and 5: Significant at p < 0.0005
    Comparing 3 and 6: Significant at p < 0.0050
    Comparing 4 and 5: Significant at p < 0.1000
    Comparing 4 and 6: Significant at p < 0.0050
    Comparing 5 and 6: Significant at p < 0.0500

Inter series comparisons (25ms pfx /da/ versus 25ms sfx /ad/):
    Comparing 0 and 0: Significant at p < -0.0100
    Comparing 0 and 1: Significant at p < -0.0005
    Comparing 0 and 2: Significant at p < -0.0005
    Comparing 0 and 3: Significant at p < -0.0250
    Comparing 0 and 4: Significant at p < -0.0050
    Comparing 0 and 5: Significant at p < -0.0500
    Comparing 0 and 6: Non-significant difference
    Comparing 1 and 0: Significant at p < 0.0005
    Comparing 1 and 1: Significant at p < 0.0050
    Comparing 1 and 2: Significant at p < 0.0005
    Comparing 1 and 3: Significant at p < 0.0005
    Comparing 1 and 4: Significant at p < 0.0005
    Comparing 1 and 5: Significant at p < 0.0005
    Comparing 1 and 6: Significant at p < 0.0005
    Comparing 2 and 0: Significant at p < 0.0250
    Comparing 2 and 1: Significant at p < 0.0005
    Comparing 2 and 2: Significant at p < 0.0005
    Comparing 2 and 3: Significant at p < 0.0005
    Comparing 2 and 4: Significant at p < 0.0005
    Comparing 2 and 5: Significant at p < 0.0005
    Comparing 2 and 6: Significant at p < 0.0005
Comparing 3 and 0: Significant at p < 0.0050
Comparing 3 and 1: Significant at p < 0.0250
Comparing 3 and 2: Significant at p < 0.0005
Comparing 3 and 3: Significant at p < 0.0005
Comparing 3 and 4: Significant at p < 0.0005
Comparing 3 and 5: Significant at p < 0.0005
Comparing 3 and 6: Significant at p < 0.0005
Comparing 4 and 0: Significant at p < 0.0050
Comparing 4 and 1: Non-significant difference
Comparing 4 and 2: Significant at p < 0.1000
Comparing 4 and 3: Significant at p < 0.0050
Comparing 4 and 4: Significant at p < 0.0050
Comparing 4 and 5: Significant at p < 0.0050
Comparing 4 and 6: Significant at p < 0.0005
Comparing 5 and 0: Significant at p < 0.0250
Comparing 5 and 1: Non-significant difference
Comparing 5 and 2: Non-significant difference
Comparing 5 and 3: Significant at p < 0.0050
Comparing 5 and 4: Significant at p < 0.0500
Comparing 5 and 5: Significant at p < 0.0050
Comparing 5 and 6: Significant at p < 0.0005
Comparing 6 and 0: Significant at p < 0.1000
Comparing 6 and 1: Significant at p < -0.1000
Comparing 6 and 2: Non-significant difference
Comparing 6 and 3: Significant at p < 0.1000
Comparing 6 and 4: Non-significant difference
Comparing 6 and 5: Significant at p < 0.0250
Comparing 6 and 6: Significant at p < 0.0050

Within series comparisons (25ms sfx /ad/):
Comparing 0 and 1: Significant at p < -0.0250
Comparing 0 and 2: Significant at p < 0.0500
Comparing 0 and 3: Non-significant difference
Comparing 0 and 4: Non-significant difference
Comparing 0 and 5: Non-significant difference
Comparing 0 and 6: Significant at p < 0.0500
Comparing 1 and 2: Significant at p < 0.1000
Comparing 1 and 3: Significant at p < 0.0050
Comparing 1 and 4: Significant at p < 0.0250
Comparing 1 and 5: Significant at p < 0.0050
Comparing 1 and 6: Significant at p < 0.0005
Comparing 2 and 3: Significant at p < 0.0250
Comparing 2 and 4: Significant at p < 0.1000
Comparing 2 and 5: Significant at p < 0.0100
Comparing 2 and 6: Significant at p < 0.0050
Comparing 3 and 4: Significant at p < -0.1000
Comparing 3 and 5: Non-significant difference
Comparing 3 and 6: Significant at p < 0.0500
Comparing 4 and 5: Significant at p < 0.0250
Comparing 4 and 6: Significant at p < 0.0050
Comparing 5 and 6: Significant at p < 0.0500
<table>
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<tr>
<th>Comparing</th>
<th>Result</th>
</tr>
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<tbody>
<tr>
<td>0 and 1</td>
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</tr>
<tr>
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<tr>
<td>0 and 3</td>
<td>Significant at p &lt; .0500</td>
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<tr>
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<td>Non-significant difference</td>
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<tr>
<td>0 and 6</td>
<td>Non-significant difference</td>
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<tr>
<td>1 and 2</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>1 and 3</td>
<td>Significant at p &lt; .0005</td>
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<td>Significant at p &lt; .1000</td>
</tr>
<tr>
<td>3 and 5</td>
<td>Significant at p &lt; .0500</td>
</tr>
<tr>
<td>3 and 6</td>
<td>Significant at p &lt; .0250</td>
</tr>
<tr>
<td>4 and 5</td>
<td>Non-significant difference</td>
</tr>
<tr>
<td>4 and 6</td>
<td>Significant at p &lt; .0500</td>
</tr>
<tr>
<td>5 and 6</td>
<td>Non-significant difference</td>
</tr>
</tbody>
</table>

**Inter series comparisons (abrupt versus gradual):**

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<th>Comparing</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Non-significant difference</td>
</tr>
<tr>
<td>0 and 1</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>0 and 2</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>0 and 3</td>
<td>Significant at p &lt; .0250</td>
</tr>
<tr>
<td>0 and 4</td>
<td>Non-significant difference</td>
</tr>
<tr>
<td>0 and 5</td>
<td>Non-significant difference</td>
</tr>
<tr>
<td>0 and 6</td>
<td>Non-significant difference</td>
</tr>
<tr>
<td>1 and 0</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>1 and 1</td>
<td>Non-significant difference</td>
</tr>
<tr>
<td>1 and 2</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>1 and 3</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>1 and 4</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>1 and 5</td>
<td>Significant at p &lt; .0005</td>
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<tr>
<td>1 and 6</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>2 and 0</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>2 and 1</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>2 and 2</td>
<td>Non-significant difference</td>
</tr>
<tr>
<td>2 and 3</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>2 and 4</td>
<td>Significant at p &lt; .0005</td>
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<td>2 and 5</td>
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</tr>
<tr>
<td>2 and 6</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>3 and 4</td>
<td>Non-significant difference</td>
</tr>
<tr>
<td>3 and 5</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>3 and 6</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>4 and 5</td>
<td>Non-significant difference</td>
</tr>
<tr>
<td>4 and 6</td>
<td>Significant at p &lt; .0005</td>
</tr>
<tr>
<td>5 and 6</td>
<td>Non-significant difference</td>
</tr>
</tbody>
</table>
Comparing 3 and 0: Significant at $p < 0.1000$
Comparing 3 and 1: Significant at $p < 0.0005$
Comparing 3 and 2: Significant at $p < 0.0005$
Comparing 3 and 3: Non-significant difference
Comparing 3 and 4: Significant at $p < 0.0250$
Comparing 3 and 5: Significant at $p < 0.0050$
Comparing 3 and 6: Significant at $p < 0.0005$
Comparing 4 and 0: Non-significant difference
Comparing 4 and 1: Significant at $p < 0.0005$
Comparing 4 and 2: Significant at $p < 0.0005$
Comparing 4 and 3: Significant at $p < 0.0500$
Comparing 4 and 4: Significant at $p < 0.0500$
Comparing 4 and 5: Significant at $p < 0.0050$
Comparing 4 and 6: Significant at $p < 0.0050$
Comparing 5 and 0: Non-significant difference
Comparing 5 and 1: Significant at $p < 0.0005$
Comparing 5 and 2: Significant at $p < 0.0005$
Comparing 5 and 3: Significant at $p < 0.0250$
Comparing 5 and 4: Non-significant difference
Comparing 5 and 5: Significant at $p < 0.1000$
Comparing 5 and 6: Significant at $p < 0.0500$
Comparing 6 and 0: Non-significant difference
Comparing 6 and 1: Significant at $p < 0.0005$
Comparing 6 and 2: Significant at $p < 0.0005$
Comparing 6 and 3: Significant at $p < 0.0100$
Comparing 6 and 4: Non-significant difference
Comparing 6 and 5: Significant at $p < 0.0050$
Comparing 6 and 6: Significant at $p < 0.0500$

Within series comparisons (gradual):
Comparing 0 and 1: Significant at $p < 0.0005$
Comparing 0 and 2: Significant at $p < 0.0005$
Comparing 0 and 3: Significant at $p < 0.0500$
Comparing 0 and 4: Non-significant difference
Comparing 0 and 5: Non-significant difference
Comparing 0 and 6: Non-significant difference
Comparing 1 and 2: Significant at $p < 0.0005$
Comparing 1 and 3: Significant at $p < 0.0005$
Comparing 1 and 4: Significant at $p < 0.0005$
Comparing 1 and 5: Significant at $p < 0.0005$
Comparing 1 and 6: Significant at $p < 0.0005$
Comparing 2 and 3: Significant at $p < 0.0005$
Comparing 2 and 4: Significant at $p < 0.0005$
Comparing 2 and 5: Significant at $p < 0.0005$
Comparing 2 and 6: Significant at $p < 0.0005$
Comparing 3 and 4: Significant at $p < 0.0050$
Comparing 3 and 5: Significant at $p < 0.0005$
Comparing 3 and 6: Significant at $p < 0.0005$
Comparing 4 and 5: Non-significant difference
Comparing 4 and 6: Non-significant difference
Comparing 5 and 6: Non-significant difference
TABLE 6

FILE: baab.ba /ba/ and /ab/ stimuli (50 ms)
dF2=50Hz, Range: F2(0)=950Hz, ..., F2(6)=1250Hz

Within series comparison (/ba/):
one tailed t-test (related) at df=4
Comparing 0 and 1: Significant at p < 0.0005
Comparing 0 and 2: Significant at p < 0.0005
Comparing 0 and 3: Significant at p < 0.0050
Comparing 0 and 4: Significant at p < 0.0250
Comparing 0 and 5: Significant at p < 0.0500
Comparing 0 and 6: Significant at p < 0.0500
Comparing 1 and 2: Significant at p < 0.0250
Comparing 1 and 3: Significant at p < 0.0500
Comparing 1 and 4: Significant at p < 0.0500
Comparing 1 and 5: Significant at p < 0.0500
Comparing 1 and 6: Significant at p < 0.1000
Comparing 2 and 3: Non-significant difference
Comparing 2 and 4: Significant at p < 0.0500
Comparing 2 and 5: Significant at p < 0.1000
Comparing 2 and 6: Significant at p < 0.1000
Comparing 3 and 4: Significant at p < 0.0500
Comparing 3 and 5: Significant at p < 0.1000
Comparing 3 and 6: Significant at p < 0.0500
Comparing 4 and 5: Non-significant difference
Comparing 4 and 6: Non-significant difference
Comparing 5 and 6: Non-significant difference

Inter series comparisons (/ba/ versus /ab/):
Comparing 0 and 0: Non-significant difference
Comparing 0 and 1: Significant at p < 0.0005
Comparing 0 and 2: Significant at p < 0.0005
Comparing 0 and 3: Significant at p < 0.0250
Comparing 0 and 4: Significant at p < 0.0500
Comparing 0 and 5: Non-significant difference
Comparing 0 and 6: Non-significant difference
Comparing 1 and 0: Significant at p < 0.0005
Comparing 1 and 1: Non-significant difference
Comparing 1 and 2: Significant at p < 0.1000
Comparing 1 and 3: Significant at p < 0.0050
Comparing 1 and 4: Significant at p < 0.0050
Comparing 1 and 5: Significant at p < 0.0500
Comparing 1 and 6: Significant at p < 0.0005
Comparing 2 and 0: Significant at p < 0.0500
Comparing 2 and 1: Non-significant difference
Comparing 2 and 2: Non-significant difference
Comparing 2 and 3: Significant at p < 0.0050
Comparing 2 and 4: Significant at p < 0.0050
Comparing 2 and 5: Significant at p < 0.0050
Comparing 2 and 6: Significant at p < 0.0005
Comparing 3 and 0: Significant at p < 0.0050
Comparing 3 and 1: Non-significant difference
Comparing 3 and 2: Non-significant difference
Comparing 3 and 3: Significant at p < 0.0050
Comparing 3 and 4: Significant at p < 0.0250
Comparing 3 and 5: Significant at p < 0.0050
Comparing 3 and 6: Significant at p < 0.0050
Comparing 4 and 0: Significant at p < 0.0250
Comparing 4 and 1: Significant at p < 0.1000
Comparing 4 and 2: Significant at p < 0.1000
Comparing 4 and 3: Significant at p < 0.1000
Comparing 4 and 4: Significant at p < 0.1000
Comparing 4 and 5: Significant at p < 0.0100
Comparing 4 and 6: Significant at p < 0.0050
Comparing 5 and 0: Significant at p < 0.0250
Comparing 5 and 1: Significant at p < 0.1000
Comparing 5 and 2: Significant at p < 0.1000
Comparing 5 and 3: Non-significant difference
Comparing 5 and 4: Non-significant difference
Comparing 5 and 5: Significant at p < 0.0100
Comparing 5 and 6: Significant at p < 0.0250
Comparing 6 and 0: Significant at p < 0.0500
Comparing 6 and 1: Significant at p < 0.1000
Comparing 6 and 2: Significant at p < 0.1000
Comparing 6 and 3: Non-significant difference
Comparing 6 and 4: Non-significant difference
Comparing 6 and 5: Significant at p < 0.0250
Comparing 6 and 6: Significant at p < 0.0250

Within series comparisons (/ab/):
Comparing 0 and 1: Significant at p < -0.0050
Comparing 0 and 2: Significant at p < -0.0050
Comparing 0 and 3: Significant at p < -0.0250
Comparing 0 and 4: Non-significant difference
Comparing 0 and 5: Non-significant difference
Comparing 0 and 6: Non-significant difference
Comparing 1 and 2: Non-significant difference
Comparing 1 and 3: Significant at p < 0.0100
Comparing 1 and 4: Significant at p < 0.0250
Comparing 1 and 5: Significant at p < 0.0050
Comparing 1 and 6: Significant at p < 0.0050
Comparing 2 and 3: Significant at p < 0.0100
Comparing 2 and 4: Significant at p < 0.0100
Comparing 2 and 5: Significant at p < 0.0050
Comparing 2 and 6: Significant at p < 0.0005
Comparing 3 and 4: Non-significant difference
Comparing 3 and 5: Significant at p < 0.0100
Comparing 3 and 6: Significant at p < 0.0050
Comparing 4 and 5: Non-significant difference
Comparing 4 and 6: Significant at p < 0.0250
Comparing 5 and 6: Significant at p < 0.1000
TABLE 7

FILE: da1633.pf /da/ stimuli with 16ms and 33ms "burst"
dF2=50Hz, Range: F2(0)=1600Hz,... F2(6)=1850Hz

Within series comparison (16ms burst /da/):
one tailed t-test (related) at df=5
Comparing 0 and 1: Significant at p < 0.0005
Comparing 0 and 2: Significant at p < 0.0050
Comparing 0 and 3: Significant at p < 0.1000
Comparing 0 and 4: Significant at p < 0.1000
Comparing 0 and 5: Non-significant difference
Comparing 0 and 6: Non-significant difference
Comparing 1 and 2: Significant at p < 0.0050
Comparing 1 and 3: Significant at p < 0.0050
Comparing 1 and 4: Significant at p < 0.0005
Comparing 1 and 5: Significant at p < 0.0005
Comparing 1 and 6: Significant at p < 0.0005
Comparing 2 and 3: Non-significant difference
Comparing 2 and 4: Significant at p < 0.0250
Comparing 2 and 5: Significant at p < 0.0050
Comparing 2 and 6: Significant at p < 0.0050
Comparing 3 and 4: Non-significant difference
Comparing 3 and 5: Significant at p < 0.1000
Comparing 3 and 6: Significant at p < 0.1000
Comparing 4 and 5: Significant at p < 0.0500
Comparing 4 and 6: Significant at p < 0.0500
Comparing 5 and 6: Non-significant difference

Inter series comparisons (16ms burst /da/ versus 33ms burst /da/):
Comparing 0 and 0: Non-significant difference
Comparing 0 and 1: Significant at p < 0.0005
Comparing 0 and 2: Significant at p < 0.0050
Comparing 0 and 3: Significant at p < 0.0250
Comparing 0 and 4: Significant at p < 0.0250
Comparing 0 and 5: Significant at p < 0.0500
Comparing 0 and 6: Non-significant difference
Comparing 1 and 0: Significant at p < 0.0005
Comparing 1 and 1: Non-significant difference
Comparing 1 and 2: Significant at p < 0.0250
Comparing 1 and 3: Significant at p < 0.0050
Comparing 1 and 4: Significant at p < 0.0005
Comparing 1 and 5: Significant at p < 0.0005
Comparing 1 and 6: Significant at p < 0.0005
Comparing 2 and 0: Significant at p < 0.0005
Comparing 2 and 1: Significant at p < 0.0050
Comparing 2 and 2: Non-significant difference
Comparing 2 and 3: Non-significant difference
Comparing 2 and 4: Significant at p < 0.0250
Comparing 2 and 5: Significant at p < 0.0250
Comparing 2 and 6: Significant at p < 0.0050
Comparing 3 and 0: Significant at p < 0.1000
Comparing 3 and 1: Significant at p < 0.0050
Comparing 3 and 2: Significant at p < 0.0250
Comparing 3 and 3: Significant at p < 0.1000
Comparing 3 and 4: Non-significant difference
Comparing 3 and 5: Non-significant difference
Comparing 3 and 6: Significant at p < 0.1000
Comparing 4 and 0: Significant at p < 0.0500
Comparing 4 and 1: Significant at p < 0.0050
Comparing 4 and 2: Significant at p < 0.0050
Comparing 4 and 3: Significant at p < 0.0250
Comparing 4 and 4: Non-significant difference
Comparing 4 and 5: Non-significant difference
Comparing 4 and 6: Significant at p < 0.0500
Comparing 5 and 0: Significant at p < 0.1000
Comparing 5 and 1: Significant at p < 0.0050
Comparing 5 and 2: Significant at p < 0.0050
Comparing 5 and 3: Significant at p < 0.0250
Comparing 5 and 4: Significant at p < 0.0250
Comparing 5 and 5: Significant at p < 0.0500
Comparing 5 and 6: Non-significant difference
Comparing 6 and 0: Significant at p < 0.1000
Comparing 6 and 1: Significant at p < 0.0050
Comparing 6 and 2: Significant at p < 0.0050
Comparing 6 and 3: Significant at p < 0.0250
Comparing 6 and 4: Significant at p < 0.0250
Comparing 6 and 5: Significant at p < 0.0500
Comparing 6 and 6: Non-significant difference

Within series comparisons (33ms burst /da/):
Comparing 0 and 1: Significant at p < 0.0050
Comparing 0 and 2: Significant at p < 0.0050
Comparing 0 and 3: Significant at p < 0.0250
Comparing 0 and 4: Significant at p < 0.0250
Comparing 0 and 5: Significant at p < 0.0500
Comparing 0 and 6: Non-significant difference
Comparing 1 and 2: Significant at p < 0.0500
Comparing 1 and 3: Significant at p < 0.0100
Comparing 1 and 4: Significant at p < 0.0050
Comparing 1 and 5: Significant at p < 0.0050
Comparing 1 and 6: Significant at p < 0.0050
Comparing 2 and 3: Significant at p < 0.0500
Comparing 2 and 4: Significant at p < 0.0100
Comparing 2 and 5: Significant at p < 0.0050
Comparing 2 and 6: Significant at p < 0.0050
Comparing 3 and 4: Significant at p < 0.0500
Comparing 3 and 5: Significant at p < 0.0500
Comparing 3 and 6: Significant at p < 0.0100
Comparing 4 and 5: Non-significant difference
Comparing 4 and 6: Significant at p < 0.0250
Comparing 5 and 6: Significant at p < 0.0500
**TABLE 8**

FILE: adda.aa  /ada/ with CV or VC differences  
dF2=100Hz, Range: F2(0)=1250Hz,... F2(6)=1850Hz

Within series comparison (/ada/ ONFP):  
one tailed t-test (related) at df= 6  
Comparing 0 and 1: Significant at p < 0.0005  
Comparing 0 and 2: Significant at p < 0.0005  
Comparing 0 and 3: Significant at p < 0.0005  
Comparing 0 and 4: Significant at p < 0.0005  
Comparing 0 and 5: Significant at p < 0.0250  
Comparing 0 and 6: Non-significant difference  
Comparing 1 and 2: Significant at p < 0.0050  
Comparing 1 and 3: Significant at p < 0.0050  
Comparing 1 and 4: Significant at p < 0.0100  
Comparing 1 and 5: Significant at p < 0.0050  
Comparing 1 and 6: Significant at p < 0.0050  
Comparing 2 and 3: Non-significant difference  
Comparing 2 and 4: Non-significant difference  
Comparing 2 and 5: Significant at p < 0.0250  
Comparing 2 and 6: Significant at p < 0.0100  
Comparing 3 and 4: Non-significant difference  
Comparing 3 and 5: Significant at p < 0.0500  
Comparing 3 and 6: Significant at p < 0.0100  
Comparing 4 and 5: Significant at p < 0.0100  
Comparing 4 and 6: Significant at p < 0.0050  
Comparing 5 and 6: Significant at p < 0.1000

Inter series comparisons (/ada/ ONFP versus /ada/ OFFP):  
Comparing 0 and 0: Non-significant difference  
Comparing 0 and 1: Significant at p < 0.0005  
Comparing 0 and 2: Significant at p < 0.0005  
Comparing 0 and 3: Significant at p < 0.0100  
Comparing 0 and 4: Significant at p < 0.0250  
Comparing 0 and 5: Significant at p < 0.1000  
Comparing 0 and 6: Non-significant difference  
Comparing 1 and 0: Significant at p < 0.0005  
Comparing 1 and 1: Significant at p < 0.1000  
Comparing 1 and 2: Significant at p < 0.0100  
Comparing 1 and 3: Significant at p < 0.0005  
Comparing 1 and 4: Significant at p < 0.0050  
Comparing 1 and 5: Significant at p < 0.0005  
Comparing 1 and 6: Significant at p < 0.0005  
Comparing 2 and 0: Significant at p < 0.0005  
Comparing 2 and 1: Significant at p < 0.1000  
Comparing 2 and 2: Non-significant difference  
Comparing 2 and 3: Significant at p < 0.0250  
Comparing 2 and 4: Significant at p < 0.0500  
Comparing 2 and 5: Significant at p < 0.0100  
Comparing 2 and 6: Significant at p < 0.0050
Comparing 3 and 0: Significant at $p < 0.0005$
Comparing 3 and 1: Significant at $p < 0.0250$
Comparing 3 and 2: Non-significant difference
Comparing 3 and 3: Significant at $p < 0.0500$
Comparing 3 and 4: Significant at $p < 0.0500$
Comparing 3 and 5: Significant at $p < 0.0100$
Comparing 3 and 6: Significant at $p < 0.0050$
Comparing 4 and 0: Significant at $p < 0.0050$
Comparing 4 and 1: Significant at $p < 0.0500$
Comparing 4 and 2: Non-significant difference
Comparing 4 and 3: Significant at $p < 0.1000$
Comparing 4 and 4: Non-significant difference
Comparing 4 and 5: Significant at $p < 0.0250$
Comparing 4 and 6: Significant at $p < 0.0050$
Comparing 5 and 0: Significant at $p < 0.0250$
Comparing 5 and 1: Significant at $p < 0.0050$
Comparing 5 and 2: Significant at $p < 0.0250$
Comparing 5 and 3: Non-significant difference
Comparing 5 and 4: Non-significant difference
Comparing 5 and 5: Non-significant difference
Comparing 5 and 6: Significant at $p < 0.0250$
Comparing 6 and 0: Significant at $p < 0.1000$
Comparing 6 and 1: Significant at $p < 0.0050$
Comparing 6 and 2: Significant at $p < 0.0250$
Comparing 6 and 3: Non-significant difference
Comparing 6 and 4: Non-significant difference
Comparing 6 and 5: Non-significant difference
Comparing 6 and 6: Non-significant difference

Within series comparisons (/ada/ OFFP):
Comparing 0 and 1: Significant at $p < 0.0005$
Comparing 0 and 2: Significant at $p < 0.0005$
Comparing 0 and 3: Significant at $p < 0.0250$
Comparing 0 and 4: Significant at $p < 0.0100$
Comparing 0 and 5: Significant at $p < 0.1000$
Comparing 0 and 6: Non-significant difference
Comparing 1 and 2: Significant at $p < 0.0050$
Comparing 1 and 3: Significant at $p < 0.0005$
Comparing 1 and 4: Significant at $p < 0.0050$
Comparing 1 and 5: Significant at $p < 0.0050$
Comparing 1 and 6: Significant at $p < 0.0050$
Comparing 2 and 3: Significant at $p < 0.0050$
Comparing 2 and 4: Significant at $p < 0.0100$
Comparing 2 and 5: Significant at $p < 0.0050$
Comparing 2 and 6: Significant at $p < 0.0050$
Comparing 3 and 4: Non-significant difference
Comparing 3 and 5: Non-significant difference
Comparing 3 and 6: Significant at $p < 0.0500$
Comparing 4 and 5: Significant at $p < 0.1000$
Comparing 4 and 6: Significant at $p < 0.0500$
Comparing 5 and 6: Non-significant difference
TABLE 9

FILE: bdureresults /Cu/ discrimination. dF2=200Hz (pair)
Range: F2(1)=600Hz,... F2(24)=1750Hz; F2 step: 50Hz

one tailed t-test (related) at df=12
Comparing 1 and 2: Significant at p < 0.0500
Comparing 1 and 3: Significant at p < 0.1000
Comparing 1 and 4: Non-significant difference
Comparing 1 and 5: Non-significant difference
Comparing 1 and 6: Non-significant difference
Comparing 1 and 7: Non-significant difference
Comparing 1 and 8: Non-significant difference
Comparing 1 and 9: Non-significant difference
Comparing 1 and 10: Non-significant difference
Comparing 1 and 11: Non-significant difference
Comparing 1 and 12: Non-significant difference
Comparing 1 and 13: Significant at p < 0.1000
Comparing 1 and 14: Non-significant difference
Comparing 1 and 15: Significant at p < 0.0100
Comparing 1 and 16: Significant at p < 0.0500
Comparing 1 and 17: Significant at p < 0.1000
Comparing 1 and 18: Non-significant difference
Comparing 1 and 19: Significant at p < 0.0250
Comparing 1 and 20: Significant at p < 0.0050
Comparing 2 and 3: Non-significant difference
Comparing 2 and 4: Significant at p < -0.0050
Comparing 2 and 5: Significant at p < -0.0500
Comparing 2 and 6: Significant at p < -0.0250
Comparing 2 and 7: Significant at p < -0.0250
Comparing 2 and 8: Significant at p < -0.0500
Comparing 2 and 9: Significant at p < -0.0250
Comparing 2 and 10: Non-significant difference
Comparing 2 and 11: Non-significant difference
Comparing 2 and 12: Non-significant difference
Comparing 2 and 13: Non-significant difference
Comparing 2 and 14: Non-significant difference
Comparing 2 and 15: Non-significant difference
Comparing 2 and 16: Non-significant difference
Comparing 2 and 17: Non-significant difference
Comparing 2 and 18: Non-significant difference
Comparing 2 and 19: Non-significant difference
Comparing 2 and 20: Non-significant difference
Comparing 3 and 4: Significant at p < -0.0005
Comparing 3 and 5: Significant at p < -0.0050
Comparing 3 and 6: Significant at p < -0.0005
Comparing 3 and 7: Significant at p < -0.0250
Comparing 3 and 8: Significant at p < -0.0500
Comparing 3 and 9: Significant at p < -0.0100
Comparing 3 and 10: Non-significant difference
Comparing 3 and 11: Non-significant difference
Comparing 3 and 12: Non-significant difference
Comparing 3 and 13: Non-significant difference
Comparing 3 and 14: Non-significant difference
Comparing 3 and 15: Significant at $p < 0.0500$
Comparing 3 and 16: Non-significant difference
Comparing 3 and 17: Non-significant difference
Comparing 3 and 18: Non-significant difference
Comparing 3 and 19: Non-significant difference
Comparing 3 and 20: Significant at $p < 0.0500$
Comparing 4 and 5: Significant at $p < 0.1000$
Comparing 4 and 6: Non-significant difference
Comparing 4 and 7: Non-significant difference
Comparing 4 and 8: Non-significant difference
Comparing 4 and 9: Non-significant difference
Comparing 4 and 10: Significant at $p < 0.1000$
Comparing 4 and 11: Significant at $p < 0.0500$
Comparing 4 and 12: Non-significant difference
Comparing 4 and 13: Significant at $p < 0.0050$
Comparing 4 and 14: Significant at $p < 0.0500$
Comparing 4 and 15: Significant at $p < 0.0005$
Comparing 4 and 16: Significant at $p < 0.0250$
Comparing 4 and 17: Significant at $p < 0.0100$
Comparing 4 and 18: Significant at $p < 0.1000$
Comparing 4 and 19: Significant at $p < 0.0050$
Comparing 4 and 20: Significant at $p < 0.0005$
Comparing 5 and 6: Non-significant difference
Comparing 5 and 7: Non-significant difference
Comparing 5 and 8: Non-significant difference
Comparing 5 and 9: Non-significant difference
Comparing 5 and 10: Non-significant difference
Comparing 5 and 11: Non-significant difference
Comparing 5 and 12: Non-significant difference
Comparing 5 and 13: Significant at $p < 0.1000$
Comparing 5 and 14: Non-significant difference
Comparing 5 and 15: Significant at $p < 0.0050$
Comparing 5 and 16: Non-significant difference
Comparing 5 and 17: Significant at $p < 0.1000$
Comparing 5 and 18: Non-significant difference
Comparing 5 and 19: Significant at $p < 0.0250$
Comparing 5 and 20: Significant at $p < 0.0250$
Comparing 6 and 7: Non-significant difference
Comparing 6 and 8: Non-significant difference
Comparing 6 and 9: Non-significant difference
Comparing 6 and 10: Non-significant difference
Comparing 6 and 11: Significant at $p < 0.1000$
Comparing 6 and 12: Non-significant difference
Comparing 6 and 13: Significant at $p < 0.0250$
Comparing 6 and 14: Significant at $p < 0.1000$
Comparing 6 and 15: Significant at $p < 0.0050$
Comparing 6 and 16: Significant at $p < 0.0500$
Comparing 6 and 17: Significant at $p < 0.0250$

$x$
Comparing 6 and 18: Non-significant difference
Comparing 6 and 19: Significant at $p < 0.0250$
Comparing 6 and 20: Significant at $p < 0.0050$
Comparing 7 and 8: Non-significant difference
Comparing 7 and 9: Non-significant difference
Comparing 7 and 10: Significant at $p < 0.1000$
Comparing 7 and 11: Significant at $p < 0.1000$
Comparing 7 and 12: Non-significant difference
Comparing 7 and 13: Significant at $p < 0.0500$
Comparing 7 and 14: Significant at $p < 0.1000$
Comparing 7 and 15: Significant at $p < 0.0050$
Comparing 7 and 16: Significant at $p < 0.0500$
Comparing 7 and 17: Significant at $p < 0.0500$
Comparing 7 and 18: Non-significant difference
Comparing 7 and 19: Significant at $p < 0.0250$
Comparing 7 and 20: Significant at $p < 0.0100$
Comparing 8 and 9: Non-significant difference
Comparing 8 and 10: Significant at $p < 0.1000$
Comparing 8 and 11: Significant at $p < 0.1000$
Comparing 8 and 12: Non-significant difference
Comparing 8 and 13: Significant at $p < 0.0500$
Comparing 8 and 14: Significant at $p < 0.1000$
Comparing 8 and 15: Significant at $p < 0.0050$
Comparing 8 and 16: Significant at $p < 0.0250$
Comparing 8 and 17: Significant at $p < 0.0250$
Comparing 8 and 18: Non-significant difference
Comparing 8 and 19: Significant at $p < 0.0100$
Comparing 8 and 20: Significant at $p < 0.0100$
Comparing 9 and 10: Significant at $p < 0.0250$
Comparing 9 and 11: Significant at $p < 0.0500$
Comparing 9 and 12: Non-significant difference
Comparing 9 and 13: Significant at $p < 0.0250$
Comparing 9 and 14: Significant at $p < 0.1000$
Comparing 9 and 15: Significant at $p < 0.0050$
Comparing 9 and 16: Significant at $p < 0.0250$
Comparing 9 and 17: Significant at $p < 0.0250$
Comparing 9 and 18: Non-significant difference
Comparing 9 and 19: Significant at $p < 0.0050$
Comparing 9 and 20: Significant at $p < 0.0050$
Comparing 10 and 11: Non-significant difference
Comparing 10 and 12: Non-significant difference
Comparing 10 and 13: Non-significant difference
Comparing 10 and 14: Non-significant difference
Comparing 10 and 15: Significant at $p < 0.0100$
Comparing 10 and 16: Significant at $p < 0.1000$
Comparing 10 and 17: Significant at $p < 0.1000$
Comparing 10 and 18: Non-significant difference
Comparing 10 and 19: Significant at $p < 0.0500$
Comparing 10 and 20: Significant at $p < 0.0250$
Comparing 11 and 12: Non-significant difference
Comparing 11 and 13: Non-significant difference
Comparing 11 and 14: Non-significant difference
Comparing 11 and 15: Significant at \( p < 0.0250 \)
Comparing 11 and 16: Non-significant difference
Comparing 11 and 17: Non-significant difference
Comparing 11 and 18: Non-significant difference
Comparing 11 and 19: Significant at \( p < 0.1000 \)
Comparing 11 and 20: Significant at \( p < 0.0250 \)
Comparing 12 and 13: Non-significant difference
Comparing 12 and 14: Non-significant difference
Comparing 12 and 15: Significant at \( p < 0.0250 \)
Comparing 12 and 16: Significant at \( p < 0.1000 \)
Comparing 12 and 17: Non-significant difference
Comparing 12 and 18: Non-significant difference
Comparing 12 and 19: Significant at \( p < 0.0500 \)
Comparing 12 and 20: Significant at \( p < 0.0500 \)
Comparing 13 and 14: Non-significant difference
Comparing 13 and 15: Significant at \( p < 0.0250 \)
Comparing 13 and 16: Non-significant difference
Comparing 13 and 17: Non-significant difference
Comparing 13 and 18: Non-significant difference
Comparing 13 and 19: Non-significant difference
Comparing 13 and 20: Significant at \( p < 0.0250 \)
Comparing 14 and 15: Significant at \( p < 0.0250 \)
Comparing 14 and 16: Non-significant difference
Comparing 14 and 17: Non-significant difference
Comparing 14 and 18: Non-significant difference
Comparing 14 and 19: Significant at \( p < 0.1000 \)
Comparing 14 and 20: Significant at \( p < 0.0500 \)
Comparing 15 and 16: Non-significant difference
Comparing 15 and 17: Non-significant difference
Comparing 15 and 18: Significant at \( p < 0.0050 \)
Comparing 15 and 19: Non-significant difference
Comparing 15 and 20: Non-significant difference
Comparing 16 and 17: Non-significant difference
Comparing 16 and 18: Significant at \( p < 0.0500 \)
Comparing 16 and 19: Non-significant difference
Comparing 16 and 20: Non-significant difference
Comparing 17 and 18: Significant at \( p < 0.1000 \)
Comparing 17 and 19: Non-significant difference
Comparing 17 and 20: Non-significant difference
Comparing 18 and 19: Significant at \( p < 0.0250 \)
Comparing 18 and 20: Significant at \( p < 0.0050 \)
Comparing 19 and 20: Non-significant difference
**TABLE 10**

FILE:bdaresults /Ca/ discrimination. dF2=1.6Bark
Range: F2(1)=606Hz,... F2(17)=1772Hz; F2 step:0.4Bark

one tailed t-test (related) at df= 4
Loading t-table...
Comparing 1 and 2: Non-significant difference
Comparing 1 and 3: Non-significant difference
Comparing 1 and 4: Significant at p <-0.0005
Comparing 1 and 5: Significant at p <-0.0050
Comparing 1 and 6: Significant at p <-0.0050
Comparing 1 and 7: Significant at p <-0.0050
Comparing 1 and 8: Significant at p <-0.0050
Comparing 1 and 9: Significant at p <-0.0050
Comparing 1 and 10: Significant at p <-0.0050
Comparing 1 and 11: Significant at p <-0.0050
Comparing 1 and 12: Significant at p <-0.0050
Comparing 1 and 13: Significant at p <-0.0050
Comparing 1 and 14: Significant at p <-0.0050
Comparing 1 and 15: Significant at p <-0.0050
Comparing 1 and 16: Significant at p <-0.0050
Comparing 1 and 17: Significant at p <-0.0050
Comparing 2 and 3: Non-significant difference
Comparing 2 and 4: Non-significant difference
Comparing 2 and 5: Significant at p <-0.0500
Comparing 2 and 6: Significant at p <-0.0500
Comparing 2 and 7: Significant at p <-0.0500
Comparing 2 and 8: Significant at p <-0.0500
Comparing 2 and 9: Significant at p <-0.0500
Comparing 2 and 10: Non-significant difference
Comparing 2 and 11: Non-significant difference
Comparing 2 and 12: Significant at p <-0.0500
Comparing 2 and 13: Significant at p <-0.0500
Comparing 2 and 14: Significant at p <-0.0500
Comparing 2 and 15: Significant at p <-0.0500
Comparing 2 and 16: Significant at p <-0.0500
Comparing 2 and 17: Significant at p <-0.0500
Comparing 3 and 4: Significant at p <-0.0500
Comparing 3 and 5: Significant at p <-0.0500
Comparing 3 and 6: Significant at p <-0.0500
Comparing 3 and 7: Significant at p <-0.0500
Comparing 3 and 8: Significant at p <-0.0500
Comparing 3 and 9: Significant at p <-0.0500
Comparing 3 and 10: Significant at p <-0.0500
Comparing 3 and 11: Significant at p <-0.0500
Comparing 3 and 12: Significant at p <-0.0500
Comparing 3 and 13: Significant at p <-0.0500
Comparing 4 and 5: Non-significant difference
Comparing 4 and 6: Significant at p <-0.0500
Comparing 4 and 7: Significant at p <-0.0500
Comparing 4 and 8: Significant at p <-0.0500
Comparing 4 and 9: Significant at p <-0.0500
Comparing 4 and 10: Non-significant difference
Comparing 4 and 11: Non-significant difference
Comparing 4 and 12: Non-significant difference
Comparing 4 and 13: Significant at p <-0.0500
Comparing 5 and 6: Significant at p <-0.0500
Comparing 5 and 7: Significant at p <-0.0500
Comparing 5 and 8: Significant at p < 0.050
Comparing 5 and 9: Significant at p < 0.050
Comparing 5 and 10: Non-significant difference
Comparing 5 and 11: Non-significant difference
Comparing 5 and 12: Non-significant difference
Comparing 5 and 13: Non-significant difference
Comparing 6 and 7: Non-significant difference
Comparing 6 and 8: Non-significant difference
Comparing 6 and 9: Non-significant difference
Comparing 6 and 10: Non-significant difference
Comparing 6 and 11: Non-significant difference
Comparing 6 and 12: Non-significant difference
Comparing 6 and 13: Non-significant difference
Comparing 7 and 8: Non-significant difference
Comparing 7 and 9: Non-significant difference
Comparing 7 and 10: Non-significant difference
Comparing 7 and 11: Non-significant difference
Comparing 7 and 12: Non-significant difference
Comparing 7 and 13: Non-significant difference
Comparing 8 and 9: Non-significant difference
Comparing 8 and 10: Significant at p < 0.050
Comparing 8 and 11: Non-significant difference
Comparing 8 and 12: Non-significant difference
Comparing 8 and 13: Non-significant difference
Comparing 9 and 10: Non-significant difference
Comparing 9 and 11: Non-significant difference
Comparing 9 and 12: Significant at p < 0.1000
Comparing 9 and 13: Non-significant difference
Comparing 10 and 11: Non-significant difference
Comparing 10 and 12: Non-significant difference
Comparing 10 and 13: Non-significant difference
Comparing 11 and 12: Non-significant difference
Comparing 11 and 13: Non-significant difference
Comparing 12 and 13: Non-significant difference
TABLE 11

Comparison between the discrimination of /Cu/ pairs and /Ca/ pairs. The stimuli are ordered from left to right, according to fig. 28 and 29. Negative values indicate better discrimination among /Ca/. 

FILES: bdureresults and bdaresults (Tables 9 and 10)

Inter series comparison:
one tailed t-test (unrelated) at df = 16
Comparing 1 and 1: Significant at p < 0.0250
Comparing 1 and 2: Non-significant difference
Comparing 1 and 3: Significant at p < 0.1000
Comparing 1 and 4: Non-significant difference
Comparing 1 and 5: Non-significant difference
Comparing 1 and 6: Significant at p < 0.0500
Comparing 1 and 7: Significant at p < 0.1000
Comparing 1 and 8: Significant at p < 0.1000
Comparing 1 and 9: Significant at p < 0.1000
Comparing 1 and 10: Non-significant difference
Comparing 1 and 11: Non-significant difference
Comparing 1 and 12: Non-significant difference
Comparing 1 and 13: Non-significant difference
Comparing 2 and 1: Non-significant difference
Comparing 2 and 2: Non-significant difference
Comparing 2 and 3: Non-significant difference
Comparing 2 and 4: Non-significant difference
Comparing 2 and 5: Significant at p < 0.0050
Comparing 2 and 6: Significant at p < 0.0100
Comparing 2 and 7: Significant at p < 0.0100
Comparing 2 and 8: Significant at p < 0.0100
Comparing 2 and 9: Significant at p < 0.0100
Comparing 2 and 10: Significant at p < 0.1000
Comparing 2 and 11: Significant at p < 0.1000
Comparing 2 and 12: Significant at p < 0.1000
Comparing 2 and 13: Significant at p < 0.0250
Comparing 3 and 1: Significant at p < 0.0250
Comparing 3 and 2: Non-significant difference
Comparing 3 and 3: Non-significant difference
Comparing 3 and 4: Significant at p < 0.1000
Comparing 3 and 5: Significant at p < 0.0100
Comparing 3 and 6: Significant at p < 0.0050
Comparing 3 and 7: Significant at p < 0.0050
Comparing 3 and 8: Significant at p < 0.0050
Comparing 3 and 9: Significant at p < 0.0050
Comparing 3 and 10: Significant at p < 0.0250
Comparing 3 and 11: Significant at p < 0.0500
Comparing 3 and 12: Significant at p < 0.0250
Comparing 3 and 13: Significant at p < 0.0050
Comparing 4 and 1: Significant at p < 0.0050
Comparing 4 and 2: Significant at p < 0.0100
Comparing 4 and 3: Significant at p < 0.0050
Comparing 4 and 4: Significant at p < 0.1000
Comparing 4 and 5: Non-significant difference
Comparing 4 and 6: Significant at p < 0.0500
Comparing 4 and 7: Non-significant difference
Comparing 4 and 8: Non-significant difference
Comparing 4 and 9: Non-significant difference
Comparing 4 and 10: Non-significant difference
Comparing 4 and 11: Non-significant difference
Comparing 4 and 12: Non-significant difference
Comparing 4 and 13: Non-significant difference
Comparing 5 and 1: Significant at p < 0.0100
Comparing 5 and 2: Significant at p < 0.1000
Comparing 5 and 3: Significant at p < 0.0500
Comparing 5 and 4: Non-significant difference
Comparing 5 and 5: Non-significant difference
Comparing 5 and 6: Significant at p < 0.0250
Comparing 5 and 7: Significant at p < 0.1000
Comparing 5 and 8: Significant at p < 0.0500
Comparing 5 and 9: Significant at p < 0.0500
Comparing 5 and 10: Non-significant difference
Comparing 5 and 11: Non-significant difference
Comparing 5 and 12: Non-significant difference
Comparing 5 and 13: Non-significant difference
Comparing 6 and 1: Significant at p < 0.0050
Comparing 6 and 2: Significant at p < 0.0250
Comparing 6 and 3: Significant at p < 0.0100
Comparing 6 and 4: Non-significant difference
Comparing 6 and 5: Non-significant difference
Comparing 6 and 6: Significant at p < 0.0500
Comparing 6 and 7: Non-significant difference
Comparing 6 and 8: Significant at p < 0.1000
Comparing 6 and 9: Significant at p < 0.1000
Comparing 6 and 10: Non-significant difference
Comparing 6 and 11: Non-significant difference
Comparing 6 and 12: Non-significant difference
Comparing 6 and 13: Non-significant difference
Comparing 7 and 1: Significant at p < 0.0050
Comparing 7 and 2: Significant at p < 0.0500
Comparing 7 and 3: Significant at p < 0.0250
Comparing 7 and 4: Non-significant difference
Comparing 7 and 5: Non-significant difference
Comparing 7 and 6: Significant at p < 0.0500
Comparing 7 and 7: Non-significant difference
Comparing 7 and 8: Significant at p < 0.1000
Comparing 7 and 9: Significant at p < 0.1000
Comparing 7 and 10: Non-significant difference
Comparing 7 and 11: Non-significant difference
Comparing 7 and 12: Non-significant difference
Comparing 7 and 13: Non-significant difference
Comparing 8 and 1: Significant at p < 0.0050
Comparing 8 and 2: Significant at $p < 0.0500$
Comparing 8 and 3: Significant at $p < 0.0250$
Comparing 8 and 4: Non-significant difference
Comparing 8 and 5: Non-significant difference
Comparing 8 and 6: Significant at $p <-0.0500$
Comparing 8 and 7: Non-significant difference
Comparing 8 and 8: Significant at $p <-0.1000$
Comparing 8 and 9: Significant at $p <-0.1000$
Comparing 8 and 10: Non-significant difference
Comparing 8 and 11: Non-significant difference
Comparing 8 and 12: Non-significant difference
Comparing 8 and 13: Non-significant difference
Comparing 9 and 1: Significant at $p < 0.0050$
Comparing 9 and 2: Significant at $p < 0.0250$
Comparing 9 and 3: Significant at $p < 0.0100$
Comparing 9 and 4: Non-significant difference
Comparing 9 and 5: Non-significant difference
Comparing 9 and 6: Significant at $p <-0.0500$
Comparing 9 and 7: Non-significant difference
Comparing 9 and 8: Non-significant difference
Comparing 9 and 9: Non-significant difference
Comparing 9 and 10: Non-significant difference
Comparing 9 and 11: Non-significant difference
Comparing 9 and 12: Non-significant difference
Comparing 9 and 13: Non-significant difference
Comparing 10 and 1: Significant at $p < 0.1000$
Comparing 10 and 2: Non-significant difference
Comparing 10 and 3: Significant at $p < 0.1000$
Comparing 10 and 4: Non-significant difference
Comparing 10 and 5: Non-significant difference
Comparing 10 and 6: Significant at $p <-0.0050$
Comparing 10 and 7: Significant at $p <-0.0250$
Comparing 10 and 8: Significant at $p <-0.0100$
Comparing 10 and 9: Significant at $p <-0.0250$
Comparing 10 and 10: Non-significant difference
Comparing 10 and 11: Non-significant difference
Comparing 10 and 12: Non-significant difference
Comparing 10 and 13: Significant at $p <-0.0500$
Comparing 11 and 1: Significant at $p < 0.0500$
Comparing 11 and 2: Non-significant difference
Comparing 11 and 3: Non-significant difference
Comparing 11 and 4: Non-significant difference
Comparing 11 and 5: Non-significant difference
Comparing 11 and 6: Significant at $p <-0.0050$
Comparing 11 and 7: Significant at $p <-0.0250$
Comparing 11 and 8: Significant at $p <-0.0100$
Comparing 11 and 9: Significant at $p <-0.0100$
Comparing 11 and 10: Non-significant difference
Comparing 11 and 11: Non-significant difference
Comparing 11 and 12: Non-significant difference
Comparing 11 and 13: Significant at $p <-0.0500$
Comparing 12 and 1: Significant at $p < 0.0500$
Comparing 12 and 2: Non-significant difference
Comparing 12 and 3: Non-significant difference
Comparing 12 and 4: Non-significant difference
Comparing 12 and 5: Non-significant difference
Comparing 12 and 6: Significant at $p < -0.0250$
Comparing 12 and 7: Significant at $p < -0.1000$
Comparing 12 and 8: Significant at $p < -0.0500$
Comparing 12 and 9: Significant at $p < -0.0500$
Comparing 12 and 10: Non-significant difference
Comparing 12 and 11: Non-significant difference
Comparing 12 and 12: Non-significant difference
Comparing 12 and 13: Non-significant difference
Comparing 13 and 1: Significant at $p < 0.0500$
Comparing 13 and 2: Non-significant difference
Comparing 13 and 3: Non-significant difference
Comparing 13 and 4: Non-significant difference
Comparing 13 and 5: Significant at $p < -0.0500$
Comparing 13 and 6: Significant at $p < -0.0005$
Comparing 13 and 7: Significant at $p < -0.0050$
Comparing 13 and 8: Significant at $p < -0.0050$
Comparing 13 and 9: Significant at $p < -0.0050$
Comparing 13 and 10: Significant at $p < -0.1000$
Comparing 13 and 11: Significant at $p < -0.1000$
Comparing 13 and 12: Significant at $p < -0.0500$
Comparing 13 and 13: Significant at $p < -0.0100$
Comparing 14 and 1: Significant at $p < 0.0500$
Comparing 14 and 2: Non-significant difference
Comparing 14 and 3: Non-significant difference
Comparing 14 and 4: Non-significant difference
Comparing 14 and 5: Non-significant difference
Comparing 14 and 6: Significant at $p < -0.0050$
Comparing 14 and 7: Significant at $p < -0.0250$
Comparing 14 and 8: Significant at $p < -0.0250$
Comparing 14 and 9: Significant at $p < -0.0250$
Comparing 14 and 10: Non-significant difference
Comparing 14 and 11: Non-significant difference
Comparing 14 and 12: Non-significant difference
Comparing 14 and 13: Non-significant difference
Comparing 15 and 1: Non-significant difference
Comparing 15 and 2: Non-significant difference
Comparing 15 and 3: Non-significant difference
Comparing 15 and 4: Significant at $p < -0.0100$
Comparing 15 and 5: Significant at $p < -0.0050$
Comparing 15 and 6: Significant at $p < -0.0005$
Comparing 15 and 7: Significant at $p < -0.0005$
Comparing 15 and 8: Significant at $p < -0.0005$
Comparing 15 and 9: Significant at $p < -0.0005$
Comparing 15 and 10: Significant at $p < -0.0050$
Comparing 15 and 11: Significant at $p < -0.0100$
Comparing 15 and 12: Significant at $p < -0.0050$
Comparing 15 and 13: Significant at $p < 0.0005$
Comparing 16 and 1: Non-significant difference
Comparing 16 and 2: Non-significant difference
Comparing 16 and 3: Non-significant difference
Comparing 16 and 4: Non-significant difference
Comparing 16 and 5: Significant at $p < 0.0500$
Comparing 16 and 6: Significant at $p < 0.0050$
Comparing 16 and 7: Significant at $p < 0.0100$
Comparing 16 and 8: Significant at $p < 0.0050$
Comparing 16 and 9: Significant at $p < 0.0050$
Comparing 16 and 10: Significant at $p < 0.0500$
Comparing 16 and 11: Significant at $p < 0.0500$
Comparing 16 and 12: Significant at $p < 0.0500$
Comparing 16 and 13: Significant at $p < 0.0250$
Comparing 17 and 1: Non-significant difference
Comparing 17 and 2: Non-significant difference
Comparing 17 and 3: Non-significant difference
Comparing 17 and 4: Non-significant difference
Comparing 17 and 5: Significant at $p < 0.0500$
Comparing 17 and 6: Significant at $p < 0.0050$
Comparing 17 and 7: Significant at $p < 0.0050$
Comparing 17 and 8: Significant at $p < 0.0050$
Comparing 17 and 9: Significant at $p < 0.0050$
Comparing 17 and 10: Significant at $p < 0.0500$
Comparing 17 and 11: Significant at $p < 0.0500$
Comparing 17 and 12: Significant at $p < 0.0500$
Comparing 17 and 13: Significant at $p < 0.0100$
Comparing 18 and 1: Significant at $p < 0.0250$
Comparing 18 and 2: Non-significant difference
Comparing 18 and 3: Significant at $p < 0.1000$
Comparing 18 and 4: Non-significant difference
Comparing 18 and 5: Non-significant difference
Comparing 18 and 6: Significant at $p < 0.0100$
Comparing 18 and 7: Significant at $p < 0.0500$
Comparing 18 and 8: Significant at $p < 0.0250$
Comparing 18 and 9: Significant at $p < 0.0250$
Comparing 18 and 10: Non-significant difference
Comparing 18 and 11: Non-significant difference
Comparing 18 and 12: Non-significant difference
Comparing 18 and 13: Significant at $p < 0.1000$
Comparing 19 and 1: Non-significant difference
Comparing 19 and 2: Non-significant difference
Comparing 19 and 3: Non-significant difference
Comparing 19 and 4: Significant at $p < 0.1000$
Comparing 19 and 5: Significant at $p < 0.0250$
Comparing 19 and 6: Significant at $p < 0.0005$
Comparing 19 and 7: Significant at $p < 0.0050$
Comparing 19 and 8: Significant at $p < 0.0050$
Comparing 19 and 9: Significant at $p < 0.0050$
Comparing 19 and 10: Significant at $p < 0.0250$
Comparing 19 and 11: Significant at $p < 0.0250$
Comparing 19 and 12: Significant at p <-0.0250
Comparing 19 and 13: Significant at p <-0.0050
Comparing 20 and 1: Non-significant difference
Comparing 20 and 2: Non-significant difference
Comparing 20 and 3: Non-significant difference
Comparing 20 and 4: Significant at p <-0.0500
Comparing 20 and 5: Significant at p <-0.0100
Comparing 20 and 6: Significant at p <-0.0005
Comparing 20 and 7: Significant at p <-0.0050
Comparing 20 and 8: Significant at p <-0.0005
Comparing 20 and 9: Significant at p <-0.0005
Comparing 20 and 10: Significant at p <-0.0100
Comparing 20 and 11: Significant at p <-0.0250
Comparing 20 and 12: Significant at p <-0.0100
Comparing 20 and 13: Significant at p <-0.0050