A PSYCHOACOUSTICAL STUDY OF THE PROCESSING AND SUBSEQUENT DETECTION OF FREQUENCY-MODULATION

by

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ABSTRACT

Evidence is provided for tuned channels in the human auditory system selectively responsive to frequency-modulation (FM). Thresholds for the detection of small changes in frequency were measured with a 2IFC procedure in two subjects at a number of frequencies. Thresholds were determined before and after exposure to various adapting-stimuli. Large elevations of threshold (often by a factor of three), and in some cases small decreases in threshold (facilitation), were found depending upon the FM parameters of the adapting-stimulus. The degree of elevation (expressed as the adaptation factor equal to the adapted threshold divided by the unadapted threshold) of sinusoidal-FM thresholds was found to be dependent upon the frequency-deviation (±ΔF) of a sinusoidal-FM adapting-stimulus with the same carrier- (F_c) and modulation-frequency (F_m) as the test-stimulus (Chapter 3). A characteristic function was found consisting of a linear increase in adaptation factor with increasing ±ΔF up to some value of ±ΔF (dependent upon F_c) after which a progressive decline in adaptation factor occurred with further increases in ±ΔF. One possible explanation of the results in terms of the processing of frequency transitions by filters in the carrier-frequency domain was examined. By assuming the existence of rectangular filters with bandwidths equal to the value of ±ΔF at which peak adaptation occurred, and by introducing a cosinusoidal function to give different weights to different rates-of-change of frequency (df/dt) of the modulating waveform, a good fit to the empirical data was found with adaptation given by the area under the modulating waveform within the filter. A central assumption of the filter model was that the fall in adaptation factor at high values of ±ΔF was due to the decreasing sweep duration within the filter as ±ΔF increased beyond the filter bandwidth. This assumption was tested using linear sweeps with

a constant df/dt for values of ±ΔF at and beyond the hypothesised filter bandwidth. The decline in adaptation still occurred even though, with these stimuli, the sweep parameters within the filter remained constant. One possibility discussed was that the decline in adaptation factor was due to the activation of lateral-inhibitory side-bands by the parts of the frequency transitions outside the filter and a concomitant suppression of filter output. Finally, a good fit to the data was given by Gaussian filters which were regarded as more realistic. The inferred filter bandwidth and their relationship to frequency were similar to critical bandwidths (Scharf, 1970) suggesting a common basis for these measures of frequency selectivity. By holding the test F_c of sinusoidal-FM constant and varying the adapting F_c, the selectivity of adaptation effects, tuning-curves, were determined (Chapter 4) and compared to measures of selectivity derived from Chapter 3. Large differences were found, the tuning-curves having markedly narrower bandwidths and a non-Gaussian shape. In Chapter 5 evidence supporting the hypothesis that adaptation is an after-effect of prolonged inhibition between FM-channels tuned to F_c and F_m was found. In the terms of this hypothesis, F_c and F_m tuning-curves represent the range and strength of lateral-inhibitory connections between neighbouring channels. Overall, the data from Chapters 3-5 was consistent with a two-stage model of F_c selectivity in FM processing, the first stage given by the derived Gaussian bandwidths and a higher stage represented by tuning-curves. Both carrier- and modulation-frequency tuning-curves showed evidence of threshold facilitation (Chapters 4 and 5). Thresholds for single linear upward frequency sweeps (up sweeps) were increased by a factor of 2 to 3 following exposure to repetitive (8 Hz) up sweeps but not following exposure to down sweeps or tone bursts; correspondingly, thresholds for down-sweep stimuli were increased only by down sweeps. Sinusoidal FM test stimulus thresholds were elevated by both up-sweeps and down-sweeps and to a lesser extent by tone bursts (Chapter 6). These results suggest the existence in the auditory system of channels specific to upward FM, downward FM, as well as AM or repetition channels. Sawtooth-FM did not reveal directional-specific adaptation effects because of the adapting influence of the rapid frequency transitions between the sweep components of sawtooth waveforms (Chapter 7).

Examination of unadapted thresholds as a function of test-stimulus duration revealed the existence of an integration time of 400 ms for the detection stage of FM processing (Chapter 8).

CONTENTS

CHAPTER 1: INTRODUCTION

1.1 General Introduction

1.1.1 Methodology

This study uses the techniques and rationale of selective adaptation to provide evidence for the processing of frequency modulation (FM) by the ear; the determination of thresholds and elevations of threshold for the detection of FM in supra-threshold stimuli, that examines the processing of FM per se and not FM stimuli, being the principle method employed.

Adaptation procedures have been used for a number of years in the study of the human visual system (e.g. Blakemore and Campbell, 1969). The basis of the methodological rationale is the belief that demonstrations of threshold elevations (other measures of adaptation like negative after-effects can be used) specific to a particular stimulus feature is evidence for a channel coding that feature. Subdivisions of this mechanism into tuned elements or channels sensitive only to restricted ranges of the dimensions defining the feature can be demonstrated. The term channel refers to the total ensemble concerned with the extraction and processing of a stimulus feature as well as tuned subdivisions of this mechanism.

Definitions of a channel usually involve a physiological metaphor, the channel being regarded as a functionally isolated, ascending, pathway of a sensory system. Feature extraction and specificity are seen as consequences of the connectivity, that is, the structural arrangement of neurones forming the channel. It is worth noting that a channel is a psychophysical entity referring to physiological mechanisms assumed to underly certain perceptual phenomena. In contrast, feature detector is the term usually applied to neurones selective for certain features of a stimulus.

Demonstration of the perceptual independence of auditory features is the crucial evidence for feature-specific channels.

In the first study of auditory mechanisms by selective adaptation Kay and Matthews (1971; 1972) demonstrated precisely this for FM. Thresholds for the detection of FM were elevated by FM adapting-stimuli only and channels tuned to restricted ranges of carrier and modulation frequency were demonstrated. There were earlier studies of complex adaptation phenomena (Rawdon-Smith and Grindley, 1935; Rosenblith, 1947; Besser, 1966), however, Kay and Matthews (1971; 1972) introduced a new method and model to auditory psychophysics, one previously used in visual psychophysics, and numerous physiological experiments demonstrating the existence of auditory neurones preferentially sensitive to certain stimulus features including FM (see Evans, 1974; Scheich, 1976, for reviews).

1.1.2 Features

For a discussion of auditory feature analysis, the primary questions must be: What is a feature and is FM one? Examination of human speech and animal vocalizations reveal the presence of discrete segments showing major features such as rapid changes of frequency (FM), amplitude (AM), noise bursts, spectral patterns, temporal patterns, etc. Scheich (1976) distinguishes between bioacoustic dimensions as "objective variable dimensions that are relevant in communication sounds of animals in general .....", and features, representing a more restricted property of significant information bearing content and closely related to the ethological concepts of inate and species-specific releasors. He lists some of the basic ideas behind the term feature:

1. An acoustic feature may be called a property of a natural sound which by itself or in the context of other properties is significant for eliciting a certain behaviour. In a wider sense, features may be those properties which are crucial for the identification of sounds with high significance for the species.
2. Not every acoustic dimension in a natural sound is of special relevance for any given species.
3. For a relevant dimension it is usually a restricted range of the whole continuum of a dimension which has behavioural significance (boundaries).

4. Upon crossing the critical boundaries along the continuum of a stimulus dimension, the stimulus may become ineffective or the behavioral response (or the psychophysical percept) may change qualitatively.

   (From Scheich, 1976, p.164)

In these terms FM would represent a bioacoustic dimension. Whether FM is a feature as defined above must be determined empirically. The demonstration of FM specific adaptation and FM selective neurones is evidence for FM as an auditory feature. This is confirmed by the tuning of adaptation effects (Kay and Matthews, 1972) corresponding to the critical boundary concept cited by Scheich (1976).

Problems arise in the isolation of the critical dimensions of auditory features of which FM is a good example, especially periodic FM. Further, in a natural situation the feature is not isolated and may be correlated with other stimulus properties as a result of stimulus transformation at the ear (e.g. loudness changes) or properties of the articulatory mechanisms. It is possible that though coded independently the covariance of two features is of perceptual importance. This may be lost through experimental control.

For the purposes of this study a feature is defined as a property of a complex acoustic signal (including speech) processed independently of other properties for the purposes of detection, recognition or identification of the signal.

There now follows a review of the literature.

1.2 Literature Survey

1.2.1 FM in Speech

FM in some form is present in all languages. A distinction can be made between variations of the fundamental frequency, the glottal period, and variations of formant frequencies, that is, formant transitions. Lehiste and Peterson (1962) provide an excellent guide to the acoustic properties of some formant transitions. Formant refers to concentrations of energy at the resonant frequencies of the vocal apparatus. Formants are assigned numbers depending on frequency, hence F1, F2, F3 refer to formants of increasing frequency of a speech signal. A formant transition refers to a change in the formant frequency over time.

There has been considerable effort directed towards determining the role of formant transitions in the perception and identification of speech sounds. Some speech adaptation experiments have addressed this question and are discussed in a separate section. Experiments not involving adaptation have led to some ambiguous and sometimes conflicting data as to the value of frequency transitions as a speech cue. Lindblom and Studdert-Kennedy (1967) found that together with the frequency "locus" of formants the direction and rate of change of transitions provided a cue to the identification of vowel sounds in a consonant-vowel-consonant syllable. Lehiste and Peterson (1961) measured the parameters of F2 transitions assumed to serve as cues to consonant identification and compared them to those serving as cues to the presence of complex syllabic nuclei (glides and dipthongs). Differences in rate of change and duration existed between transitions providing a possible basis for identification. The temporal properties of F1 and F2 transitions were found by Liberman et al (1956) to be a cue distinguishing between members of the series vowel-semivowel and vowel-vowels of changing "colour".

A change in duration was found to produce a change in the category to which Ss assigned a sound. A second experiment determined that duration and not rate of change was the critical variable. Whether the existence of a transition was necessary is unclear.

Stevens and Klatt (1974) reported that transitions acted as cues to the voiced-voiceless distinction for stop consonants and could be traded with another cue, voice-onset time (VOT). A study by Summerfield and Haggard (1977) found that the F1 onset frequency and not the transition per se was a cue to voicing. They did suggest, however, that a rising F1 predisposed a consonantal percept which a transitionless F1 with the same onset frequency did not.

It seems certain that format transitions act as cues though their role may be secondary.

The role of variations in fundamental frequency, pitch fluctuations, are unambiguous. These have two major linguistic functions. First, pitch fluctuations occur across sentences, the pattern being referred to as the intonation contour. The fundamental frequency is usually in the range 80-300Hz with women higher than men and the range of the transitions can reach 100 Hz. Rates of change of frequency are rather low. The intonation contour is the primary acoustic cue in many languages, including English, for the identification of utterances as questions or statements (Lieberman, 1967). The emotional state of the speaker is also coded in the intonation contour (Lieberman, 1967). Abe (1962) notes the importance of intonation in English calls. Second, pitch fluctuations occur within a word referred to as tone. Thus a distinction can be made between nontonal languages (e.g. English) and tone languages (e.g. Chinese). The character of a pitch fluctuation within a word of a tone language often determines the meaning of the word, i.e. pitch fluctuations in tone languages produce differences in meaning of an utterance that are lexical, in intonation the differences are syntactical (Abercrombie, 1967).

1.2.2 Animal Vocalizations

FM is a common property of the vocalizations of numerous species including the squirrel monkey (see Winter and Funkenstein, 1973), the cat (see Watenabe and Ogushi, 1968), birds (Marler, 1955; Stein, 1968; and see Scheich et al, 1977), the treefrog (Narins, 1976), and bats, rodents, insects and cetacea (Sales and Pye, 1974).

1.3 Review of the Neurophysiological Literature

1.3.1 Lower Levels of the Auditory Pathway

In the cochlear nucleus (CN), but not the cochlear nerve, a number of units have been found showing a preference for one direction of frequency change, a phenomenon first reported by Evans and Nelson (1966b) in the cat. This finding has been replicated by a number of studies (Erulkar et al, 1968, in the cat; Fernald and Gerstein, 1972, in the cat; Moller, 1974a,b, in the rat; and Britt and Starr, 1976, in the cat). Only two studies (Moller, 1969; Watenabe, 1972) have reported no directional preferences in CN units, in the rat and cat respectively. The selectivity, when found, varies in extent and takes the form of an asymmetrical firing density in the response patterns to up or down sweeps rather than an all-or-none response. From the studies quoted above that give the number of units studied and those having a asymmetrical response it can be calculated that only 16% of a total of 319 units are asymmetrical. Further, asymmetrical units are more prevalent in the dorsal CN (Evans, 1975). Most asymmetrical units prefer falling sweeps (Erulkar et al, 1968; Moller, 1974a,b). None of the units in the CN are "feature-detectors" in the sense that they respond only to FM stimuli and responses are largely predictable from the steady-state (pure-tone) response areas of the unit. Evans (1975) discusses directional selectivity as reflecting the asymmetrical distribution of inhibitory response areas around the excitatory areas of CN units. This asymmetry is manifest in the time delays as well as the extent of side-bands. Further, Evans and Nelson (1966a,b) found little difference in threshold between FM, AM and pure-tones.

Responses to periodic FM are also predictable but could form the basis for the coding of modulation frequency. For periodic FM crossing the high frequency edge of a response area a phase-locked periodic unit response occurs slightly leading the modulation waveform. The maximum spike density is at the lowest frequency of the waveform, i.e. the furthest excusion into the response area. For excursions across the low frequency edge of the response area a similar pattern is evoked but with an inverted relationship to the modulation waveform. For excursions entirely within the response area a bimodal response distribution occurs (see Evans, 1975, Fig. 38A-J).

Unit responses in the CN to rate of change of frequency show preferences for certain rates, reflecting the time spent by the sweep in the response area (Moller, 1969, 1974a,b). At certain rates of change the response pattern becomes localized around the unit characteristic frequency (CF), and the amplitude histogram peak height increases, enhancing the response to a particular range of rates of change.

Watenabe (1972) found that in contrast to the CN preferential responses to direction of frequency change in the superior olive favour upward sweeps. This has been found in all the studies of the inferior colliculus (IC) examining directional selectivity (Watenabe and Ogushi, 1968; and Watenabe, 1972, in the cat; Clopton and Winfield, 1974, and Vartanian, 1974, in the rat). This shift of preference from down to upward sweeps may simply be a sampling artifact. However, Clopton and Winfield (1976) found exposure to patterns of upward frequency sweeps and noise bursts could alter the selectivity of IC units from down-selective to up-selective in young rats. All unexposed units were down-selective. This suggests the selectivity at the IC may have a functional basis and involve additional factors to those present at the CN.

Watenabe and Ogushi (1968) and Watenabe (1972) reported directional selectivity contingent upon rate-of-change of frequency with ascending units tuned to high rates and descending units to low rates. The FM properties required for maximum responsiveness were similar to those naturally occurring in cat vocalizations.

Nelson et al (1966) found responses tuned to the modulation frequency of AM and FM in the IC of the cat. Most responses including directional selectivity were predictable from steady-state responses. A very few units did show unpredictable responses, for instance, a unit responding only to sweeps outside its pure-tone response area.

Vartanian (1974) determined IC unit responses in the rat to frequency sweeps after first determining the steady-state excitatory response areas (with a pure-tone) and inhibitory areas by a two-tone method. As the interval between tones increased the inhibitory bandwidth decreased. Thus the temporal characteristics of a stimulus determine the frequency range of inhibitory effects. The unit response to sweeps and preferences for certain rates of change of frequency was dependent upon the time course and frequency range of sweeps vis-a-vis the excitatory and inhibitory response areas of the unit. This is essentially the model proposed by Evans (1975) for directional selectivity in the CN. At the IC, however, it may not be entirely adequate. First, there is the shift in preference from down-to up-sweeps between the CN and IC. The results of Clopton and Winfield (1976), discussed earlier, suggest this is not due to sampling of units. Second, inhibitory processes are more prevalent in the IC, reflected in the number of onset units found there (Erulkar, 1975). This suggests an activation of both excitatory and inhibitory processes by stimuli in a units response area. Both pre- and post-synaptic inhibitory mechanisms have been found in the IC (Erulkar, 1975). The role of inhibitory processes in direction selectivity was examined by Watenabe (1972). For example, up selectivity was characterised by an EPSP followed by an IPSP for up-sweeps and the reverse for down-sweeps. Such a unit would show little response to down sweeps. The temporal patterning of synaptic events would seem to form the basis of directional selectivity in this case. Third, the asymmetry of inhibitory side-bands does not seem to change significantly from the CN to the IC. This may be reflected in the down selectivity of unexposed IC units in young rats (Clopton and Winfield, 1976). The final experimentally determined functional selectivity (Watenabe and Ogushi, 1968) may be determined by mechanisms described by Watenabe (1972).

1.3.2 The Auditory Cortex

The responses of many auditory cortical units are complex compared to those at lower levels. A large proportion of units are concerned with the temporal and spatial characteristics of stimuli and can be described as "feature-detectors". Frequency selectivity is reduced by comparisons with lower levels as is tonotopic organisation (Evans, 1968), though this latter concept as applied to the cortex is showing signs of rehabilitation (Merzenich et al, 1976). Ablation studies of the auditory cortex (Neff, Diamond & Cassedy, 1975) show that the discrimination of differences in frequency and intensity between tones, seen as based on tonotopic organisation, are largely unimpaired by bilateral cortical ablation. Discrimination between temporal patterns of tones, tones of different duration and between the spatial locations of tones are impaired.

Evans and Whitfield (1964) found 6 units in the primary auditory cortex of the cat (4% of the population studied) responsive only to FM tones. Another 21% responded only to clicks and odd sounds (e.g. the jangling of keys). Whitfield and Evans (1965) studied the responses of auditory cortical units to sinusoidal and ramp FM in the unanaesthetised, unrestrained cat. In the majority of units responsive to FM this response was greater than that to steady tones, and, in 10% no response to steady tones was found. Periodic responses phase-locked to the modulation waveform of sinusoidal FM occurred and in many units this response occurred to one direction of frequency change. This was confirmed with ramp stimuli, that is, units were direction specific in contrast to the direction preferences found at lower levels. Some units showed complex directional responses to down-sweeps in the high frequency portion of the response area and up-sweeps in the low frequency portion. Some responses to FM were predictable from steady-state responses in that a unit would only respond to sweeps within the pure-tone response area. The majority were unpredictable with FM response bandwidths wider than the pure-tone response area, if present. These are comparable to the units found by Nelson et al (1966) in the IC of the cat.

Feher and Whitfield (1966) reported auditory cortical units in the cat responsive only to an FM tone and steady tone presented simultaneously but not to either alone.

Evans and Jolley (cited in Evans, 1974) found cortical units in the cat tuned to a narrow range of modulation frequences and comparable to the psychophysical tuning curves of Kay and Matthews (1972) discussed in the next section.

Goldstein et al (1968) found only one FM specific unit in 131 studied in the cat. Watenabe (1972) in a study of 11 cortical units in three cats reported no FM specific units though directional preferences to FM and AM sweeps were found.

Kelly and Whitfield (1971) used a shock-avoidance task to measure the discrimination between rising and falling FM ramps, in cats, before and after bilateral cortical lesions. Animals could still perform the discrimination after ablation but with the following deficits: (a) a longer number of sessions was needed to reach maximum performance; (b) more spontaneous responses occurred; (c) there was greater variability across sessions, i.e. difficulty in maintaining response level. Discrimination of the direction of frequency change was thus immune to cortical ablations suggesting that performance could be mediated by the less refined FM processing capacities at lower levels. The authors suggested that the deficits found reflected the limited access of lower levels to processing centres.

Swarbrick and Whitfield (1972) measured unit responses in the cat to wide-band noise amplitude-modulated by a triangular waveform. Of a population of 30 units two small groups exhibited complex response properties. The first responsed with twin peaks when the ratio of fall-time to rise-time of the triangular envelope was greater than 5 to 1. The other preferred symmetrical envelopes, the responses decreasing with increasing asymmetry.

Evans (1974) discusses units in the cortex and lower levels of the auditory system sensitive to stimulus parameters defining sound source location such as time delays and interaural intensity differences. Evans (1968) found that the majority of units in the cortex of the unanaethetised, unrestrained cat show a preference for a certain location. A further 31% required a certain location for any response. Sovijarvi and Hyvarinen (1974) studied the responses of cortical units in the cat to aspects of stimulus spatial characteristics. 52% of units were responsive to spatial characteristics, 32% were responsive to the direction of sound on source movement. Directional responses were best for movement in restricted sectors of the field.

In summary, the auditory cortex is the location in the auditory pathway where a significant number of units can be characterised as feature-detectors. Responses are largely unpredictable from steady-state response characteristics, if any, and are concerned with complex time-varying and spatial characteristics of stimuli.

1.3.3 Animal Vocalizations

A number of studies have been concerned with the neural coding of biologically significant sounds, that is, animal vocalizations. Species calls are highly complex sound patterns consisting of formants, formant transitions, periodic FM, FM chirps, AM, noise bands and complex temporal and spectral patterns.

A. Squirrel Monkey

Wollberg and Newman (1972) recorded the responses of 213 neurones in the superior temporal gyrus of the awake squirrel monkey (see Winter and Funkenstein, 1973, for examples of species vocalizations). Over 80% responded to vocalizations. Some units responded reliably to one call type, others to most of the representative sample of call types used. The majority of units fell between these extremes and responded to synthetic stimuli (clicks, tones and noise). Analysis of the critical features of the vocalizations were reported for two cells. The first cell responded to all the calls; the other to one call, the isolation peep, only. Other calls produced suppression of this units response. Analysis was carried out by isolating temporal segments of the call. For the first cell (the multiple responder) it was found that temporal segments of an isolation peep had corresponding discrete response components. Earlier parts of the call interacted with later segments to determine the response to these segments, i.e. temporal structure and interaction were of importance. The full response was modified by deletion. The second call seemed concerned with particular segments of the call with parts of the call coded in terms of the effect on responses to later components. Newman and Wollberg (1973) found similar results with 90% of a population of 83 units responding to vocalizations. A wide range of response probabilities and specificities were found with 89% of units responding to more than half of the 12 different vocalizations. Response patterns to a single call differed between cells. A number of units responded to calls representing several call groups but not to acoustically similar calls, for example, calls with similar frequency transitions. This suggests cells were not simple feature analysers responding to say FM in the vocalization. Winter and Funkenstein (1973) recorded responses from the awake animal to species-specific vocalizations, FM tones, tones, clicks and noise. Of 116 units responding to calls, 48 were analysed further, these being units exhibiting a reproducible response pattern correlated in time with the onset of the stimulus. In 63% of this group the response to calls could be predicted from the unit response to steady-state tones, that is, on the basis of spectral overlap of response areas and call patterns. A further 37% had unpredictable responses and a number of units (7% of 116 units) responded only to calls. Of 96% of units tested with all stimulus classes only about 4% displayed selective responses to a stimulus category, including FM. No responses to vocalizations based on acoustic features seemed to be present though a class of units responsed only to calls containing FM. These could be FM selective units as described by Whitfield and Evans (1965) or receive input from such cells.

Hupfer et al (1977) trained monkeys to discriminate between species-specific vocalizations and complex sound patterns similar to vocalizations. Performance was determined after total and partial bilateral ablation of the auditory cortex. No change in performance was seen after small lesions of the superior temporal gyrus. Medium lesions led to deficits in retention after retraining with animals being unable to reach criterion level though performance was above chance level. Animals could not carry out the task after total destruction of the cortex, nor discriminate between calls and white noise. However these animals could learn to jump off a perch to a call. This would suggest some ability to recognize calls was present, presumably mediated by centres lower in the auditory pathway.

B. Cat

Watenabe and Katsuki (1974) determined responses of units at various levels of the auditory system to cat vocalizations. Band-pass filtering was employed to determine the critical spectral segments for response. At all levels of the auditory pathway, including the cortex, responses were largely predictable from steady-state responses. Inhibitory effects reflecting the presence of spectral energy within inhibitory side-bands was also found. Some units responded only to filtered vocalizations as a result of these inhibitory mechanisms. The theoretical premise of the study was that inhibition played a role in the extraction of features within limited spectral regions. Sovijarvi (1975) studied 132 cortical units to tones, species-specific vocalizations and complex sounds including bird vocalizations. Most units had responses predictable from pure-tone response though 22% did not respond to pure-tones. Of these the majority responded to specific types of natural sounds. A number of units showed specific responses to hand-claps, jangling of keys, etc. in line with Whitfield and Evans (1965).

C. Birds

Similar data to that found in the squirrel monkey has been reported by Scheich et al (1977) for the auditory midbrain nucleus of the Guinea Fowl. This nucleus is the analogue of the mammalian inferior colliculus (Campbell and Boord, 1974). Of special interest were units capable of detecting frequency complexes and harmonic spectra.

1.3.4 Response Plasticity

The phenomenon of response plasticity is important because changes in response including feature specificity have been found to be dependent upon an animal's behavioural state. Further apparently spontaneous changes in response properties can occur. The importance of anaesthetic state has also been noted (Evans and Nelson, 1973; Evans, 1974).

Evans and Whitfield (1964) reported response plasticity and habituation in the primary auditory cortex of unanaethetised, unrestrained cats. Response categories were seen to change over time with transient responses increasing in proportion to sustained responses over the initial period of recording. Goldstein et al (1968) reported response plasticity in the proportion of 1 in 5 units in unanaethetised cats. In some cases changes in response selectivity occurred. Habituation was also observed. Evans (1968) reported changes in a cortical unit from sustained excitation to sustained inhibition. Evans (1968; 1974) discussed the role of attention on the responses of auditory units. Sovijarvi (1975) found habituation in the response of auditory cortical units in the cat to natural sounds including cat vocalizations.

Pfingst et al (1977) measured the dependence of unit responses in the Rhesus monkey upon behavioural state. Stimuli were pure-tones. Four behavioural states were used: (1) awake and performing a reaction time task; (2) awake without the task; (3) drowsy sleep; (4) with non-barbiturate anaesthetic. In the majority of units responses were greatest in the performance condition. The responses in the awake condition were greater than the sleep condition which in turn were greater than the anaethetised condition. The form of spike rate vs intensity curves was also different.

Manley and Muller-Preufs (1978) studied the response variability of cortical units in the anaethetised squirrel monkey. In all 63 units were studied in the primary cortex and 43 in the secondary cortex. Cells were tested repeatedly over a number of hours. In the primary cortex 40% of units showed a change in response strength over repeated vocalizations, 10% a change in response pattern and 20% a change in selectivity. In the secondary cortex the proportions were 44%, 14% and 42% respectively.

Further plasticity may result from connections between vocalization control and production centres and auditory processing centres (for example see Zaretsky, 1978). Schuller (1979) in the bat found a number of units whose responses to the bats own vocalization differed from that to identical artificial vocalizations. Two neurones encoded the FM of an artificial echo during vocalization only. This interaction was not acoustic but neural in origin. The interaction may be specific to echo-locating bats, however.

In summary, the properties of units in the auditory cortex or, rather, the neural organisation determining these properties are capable of modification dependent upon various factors. Though the results of Pfingst et al (1977) may reflect the general activation of neural networks, other findings, including changes in feature specificity, may reflect more fundamental, and functionally important aspects of feature analysis related to external factors as well as physiological states. Habituation, neural and behavioural, is of special interest in that it may be related to psychophysical adaptation.

1.3.5 Summary

Evidence for individual neurones capable of detecting complex properties of auditory stimuli have been described in the auditory cortex. Recognition of certain complex features can be mediated by lower centres (Kelly and Whitfield, 1971; Hupfer et al, 1977) to some extent. In addition to the stimulus properties discussed above, auditory neurones can also signal the gross temporal aspects of stimuli such as: Has the stimulus commenced? Has it ended? Is it still occurring? Neurones capable of this are transient onset, transient off-set and sustained response units. Further, neurones with an on-set and off-set response signal the duration of a sustained stimulus or the temporal character, within limits, of an intermittent stimulus.

1.4 Psychoacoustical Selective Adaptation

1.4.1 FM and AM

Using a YES/NO procedure Kay and Matthews (1971) reported elevations of sinusoidal FM thresholds following exposure to a 10 second sinusoidal FM (adapting) tone with a frequency deviation of ±40 Hz. Both test and adapting stimuli had a carrier frequency (F_c) of 0.25 kHz. The adaptation was tuned to modulation frequency (F_m) the effect becoming smaller as the separation between the adapting F_m and test F_m of 8 Hz increased. Adaptation occurred monotically,diotically and contra-aurally. In an extension of this study Kay and Matthews (1972) found thresholds elevated by a factor of 3 after exposure to a 12 second adapting stimulus. Adaptation increased with increasing duration of the adapting stimulus up to a duration of 12 seconds. The effect decayed exponentially with a time constant of 19 seconds. Tuning curves for modulation frequency were demonstrated at a number of frequencies between 1.0 and 80 Hz (Fig. 1.1a). The effect was also tuned to carrier frequency with a bandwidth of about twice the corresponding critical bandwidth at 0.25 kHz reported by Scharf (1970) (Fig. 1.1b). The effect was selective to FM,sinusoidal-AM adapting stimuli producing no elevations of thresholds,though FM did elevate AM thresholds. This effect was almost as large as the effects of AM upon AM. It was concluded that FM specific channels existed,tuned to carrier and modulation frequency. Contra-aural transfer of the effect suggested a central location for the mechanism of adaptation.

Further data were presented by Green and Kay (1973, 1974) for an f_c of 1 kHz. In the 1973 report,elevations of sinusoidal FM thresholds were measured over a wide range of modulation frequencies for various adapting modulating waveforms. The effect of square-wave FM upon sinusoidal FM thresholds was less than that for sinusoidal and triangular FM adaptors and did not transfer contra-aurally. The 1974 study reported similar findings for square-wave AM.

Fig. 1.1: Taken from Kay and Matthews (1972)

(a) Tuning curves for modulation frequency

(b) Tuning to carrier frequency

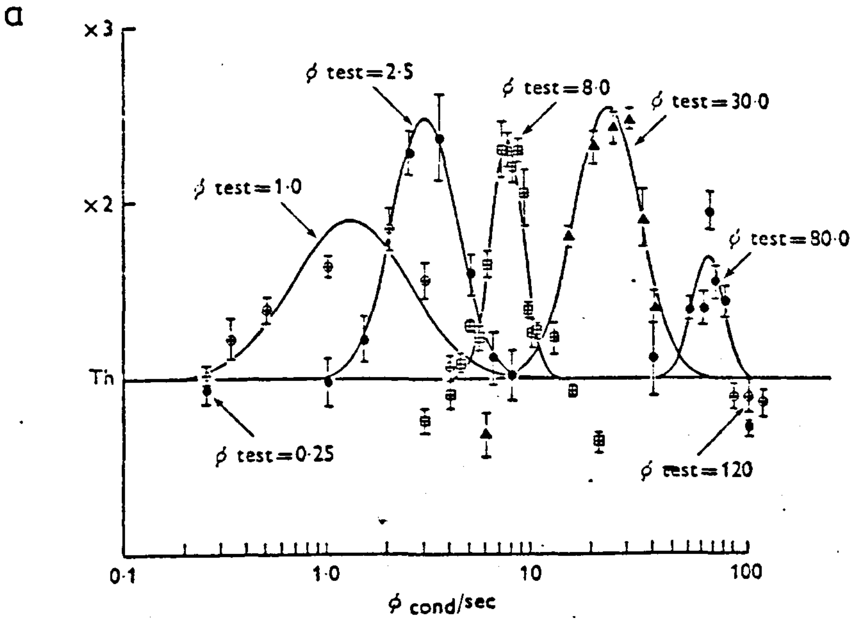


Fig. 6. The tuning of conditioning at modulation frequencies between 0·25/sec and 120/sec. Ordinate: deterioration in detection sensitivity (× threshold) for named test modulation frequencies. Abscissa: conditioning modulation-frequency: logarithmic scale.

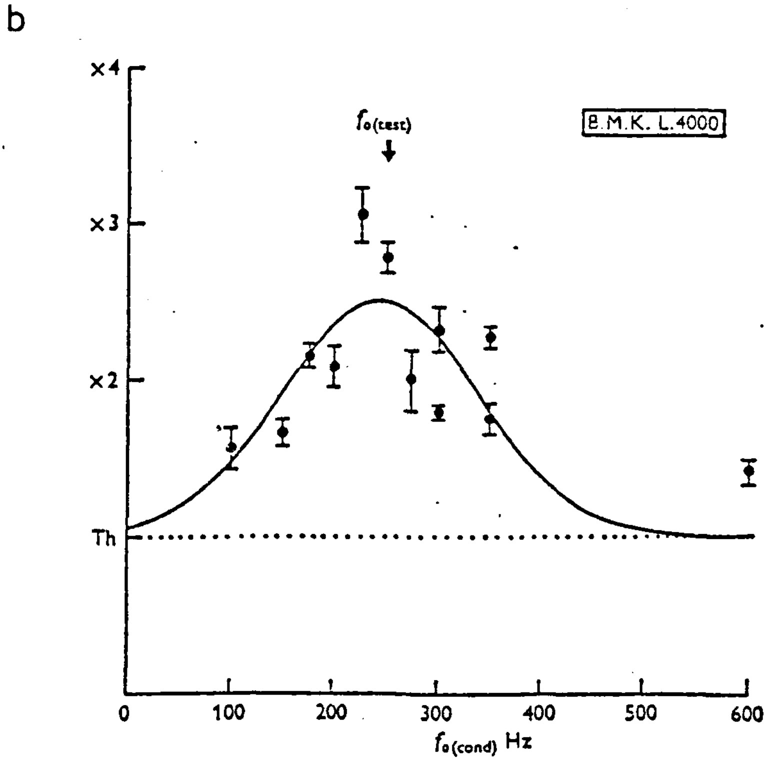


Fig. 7. Conditioning as a function of carrier frequency of the conditioning tone. Ordinate: deterioration in detection sensitivity (× threshold) of a test modulation ϕ_{test} = 8/sec of carrier-frequency, f_0, 250 Hz. Abscissa: conditioning carrier-frequency ($f_{0\,cond}$), the conditioning modulation-frequency being 8/sec throughout. Miss Lim Irene Kay Han acted as a fourth subject here.

The authors reported a functional dichotomy at 10 Hz believing that below 10 Hz was a predominantly central mechanism concerned with the rate of change of frequency of the modulating waveform. Evidence for this was the reduced effect of adapting square-wave FM compared to triangular FM below 10 Hz, the difference in rate of change of frequency between squares and sinusoidal FM being greater than the difference between triangular and sinusoidal FM. Above 10 Hz was a peripheral mechanism concerned with the periodicity of waveforms. Evidence for this was the lack of contra-aural transfer of the square-wave adaptation (therefore peripheral) and the relatively greater effects of square-wave FM above 10 Hz than below 10 Hz. Above 10 Hz adapting square-wave FM was 80% as effective as triangular FM and only 20% below.

A number of points need to be made here. The figure of 10 Hz is rather high,inspection of the data of the 1973 study show a separation between diotic and contra-aural square-wave adaptation at 3 Hz with diotic adaptation increasing to a maximum at 10 Hz. At and above this value the effect of square-wave FM is equal to sinusoidal FM. Second. there is no clear cut dichotomy at 10 Hz, rather the change is gradual over a range of modulation frequencies between 3 Hz and 10 Hz. Third, examination of the data shows square-wave to be only 25% as effective as triangular at 1 Hz and 50% as effective at 6 Hz. Corresponding percentages for square-wave and sinusoidal FM are 33% and 61%. The implication is that triangular FM is a more effective adaptor of sinusoidal FM thresholds than sinusoidal FM itself (this is, in fact, true for every frequency tested). This is clearly inconsistent with the predictions of the rate of change model as stated. However a model applying less weight to the low and zero rate of change portions of the sinusoidal waveform might account for this (this is discussed later). Fourth, the existence of diotic and contra-aural tuning curves below 10 Hz (see Fig. 1. a) shows the periodicity mechanism is operating below this frequency and has a central component. Fifth, studies of FM adaptation including this one (see later) show differences in rate of change of frequency between adapting and test stimuli to be of little importance, ie. the system is insensitive to all but very large differences in rate of change of frequency.

In an elegant experiment Green and Kay (1976) reported that the threshold for a 40 Hz sinusoidally modulated test at 1 kHz was elevated by exposure to a randomly (noise) modulated stimulus. As the pass-band (f_c = 40 Hz) of the adapting modulation was decreased the adaptation increased. Maximum adaptation was at a pass-band width of about the jnd for modulation rate. The authors concluded that this was evidence for lateral inhibitory connections between f_m tuned channels because wider pass-bands would result in greater activity in adjacent channels. This would lead to less activity in the test channel and therefore less adaptation. Results from the present study show that the situation is more complicated with inhibition implicated as the mechanism of adaptation.

Using the method of adjustment Regan and Tansley (1979) carried out adaptation experiments for FM and AM at 0.5 kHz using 2 Hz sinusoidal modulation. Using small frequency deviations (±0.4 Hz to ±2 Hz) they found large FM threshold elevations after 20 minutes adaptation. This is a surprisingly large time possibly due to the small frequency deviations employed. The effect of FM upon FM thresholds was as predicted from Kay and Matthews (1972). However for half the subjects significant elevations of AM thresholds by FM adapting stimuli occurred at some values of ΔF. Though large they were always smaller than FM threshold elevations. Similarly AM adapting stimuli produced large AM threshold elevations and significant elevations of FM thresholds, more pronounced for the S's who showed elevation of AM thresholds by FM. Quasi-FM adapting stimuli controlled for spectral factors once again produced significant and large elevations of AM thresholds for the same Ss. These violations of the specificity of adaptation effects are discussed below. Using a 2AFC procedure the authors confirmed their main finding and found threshold elevation to increase with increasing frequency deviation. The elevations of AM threshold by FM stimuli at 2 Hz seemed reduced for the one S common to both experimental procedures. At a modulation rate of 8 Hz AM elevations by FM were more pronounced (cf. Kay and Matthews, 1972). This is discussed in more detail in later chapters in the light of experimental findings.

Gardner and Wilson (1979) reported direction specific effects in FM adaptation. Tone bursts (an AM stimulus) were found to elevate sinusoidal FM thresholds but not linear sweep FM thresholds. Because the data presented in that paper is drawn from the present study it will not be discussed here.

Tansley and Regan (1980) used the method of adjustment and a YES/NO procedure at 0.5 kHz to measure threshold elevations for unidirectional frequency and amplitude ramps. Frequency deviations of the adapting stimuli were ten times the unadapted threshold. Directional specificity was established for both FM and AM. A slight decrease (facilitation) of threshold was found for test stimuli of the opposite direction. However, as in Regan and Tansley (1979) FM adaptation produced significant and large (up to a factor of 3) elevations of AM threshold with the same direction of change as the adapting stimulus for both Ss. The facilitation effect was also found for AM tests in the opposite direction. Only a small effect of AM upon FM was found for one S for upward AM only. The pattern of results was the same for the method of adjustment and YES/NO procedures.

Regan and Tansley (1979) and Tansley and Regan (1980) proposed a model in which a frequency selective analysis (critical bands) is followed by a feature specific analysis (separate channels for FM and AM) the output of which forms the input to a detection stage.

The specificity of adaptation necessary to support the hypothesis of separate channels was not found in: (a) Kay and Matthews (1972) where FM elevated AM thresholds but not vice versa; (b) Regan and Tansley (1979) where FM elevated AM thresholds and vice versa for two of four subjects. FM with small frequency deviations and quasi-FM were most effective(c) Gardner and Wilson (1979) where AM elevated sinusoidal FM thresholds but not linear sweep thresholds; (d) Tansley and Regan (1980) where unidirectional FM elevated AM thresholds with the same direction of sweep. AM did not elevate FM thresholds.

Dismissing the possibility of common channels coding FM and AM (reasons for which are given in the next section) the effects of AM upon FM thresholds could be: (1) that AM in the FM test stimulus acts as a cue to detection of the test and is degraded (adapted) by the AM adapting stimulus; (2) FM in the AM adapting stimulus affects FM thresholds; (3) both the above factors are present. Similarly the effect of FM upon AM might be: (1) adaptation of FM in the AM test stimulus which acts as a cue to the detection of test; (2) AM in the FM adaptor elevating the threshold; (3) both of the above factors. None of this is inconsistent with the model proposed by Regan and Tansley (1979) and Tansley and Regan (1980) in which the detection stage receives its input from separate FM and AM channels.

Variations in loudness associated with frequency changes can be represented by the equal loudness contour (ELC) and variations in pitch associated with amplitude changes by the equal pitch contour (EPC). Coninx (1978a,b) discusses the role of the ELC and EPC in the detection of combined differences in amplitude and frequency which is discussed later.

Differences in the precise nature of cross adaptation effects between studies may simply reflect inter-subject variations. For example, Regan and Tansley (1979) report effects of AM upon FM at 0.5 kHz for two Ss only, and only at small frequency deviations. This may simply reflect individual differences and the precise form of the ELC and/or EPC. For instance, the ELC may only be significant in a restricted range around 0.5 kHz. At larger frequency deviations at the same modulation frequency, temporal compression of the loudness changes would occur with a consequent reduced role for this cue.

The role of the ELC and EPC is discussed later as is an alternative hypothesis presented in Gardner and Wilson (1979) proposing a separate repetition channel.

Other points arising out of this review and discussed later are the role of psychophysical procedure, the mechanism underlying adaptation and tuning curves and the insensitivity of FM channels to rate of change of frequency, reflected in the large differences in this variable between test and adapting stimuli in the above.

1.4.2 Movement Detection

A series of short papers (Green and Kay, 1975; Green, Heffer and Ross, 1976; Heffer, 1978) suggested the existence of mechanisms selective to the direction of sound source movement. The threshold for detection of sound source movement, in terms of variable interaural phase difference, was elevated by exposure to large interaural differences resulting in movement in the same direction as the test stimulus (Heffer, 1978).

Grantham and Wightman (1979) reported auditory motion after-effects analogous to visual motion after-effects (the waterfall phenomenon). At 0.5 kHz adaptation to a sound source moving in the horizontal plane at a certain speed in a single direction resulted in a test stimulus being judged (by a 2 AFC right-left procedure) as moving in the opposite direction. Movement was produced by combinations of interaural time and intensity differences. The effect combined with real movement of the test stimulus such that the perception of movement was cancelled or enhanced depending on whether the test movement was in the same or the opposite direction as the adapting movement. The size of the effect increased with increasing speed of movement up to a maximum at 200 deg/sec. At 2.0 kHz no effect was present at this speed (the only one tested). The effect was not as strong as the visual after-effects decaying within one to three seconds and non-existent at low speeds for some Ss. A model in terms of motion analysers selective to direction of motion was proposed.

1.4.3 Loudness Illusions

Rawdon-Smith and Grindley (1935) reported a loudness illusion at 2.0 kHz. Subjects reported a steady increase in loudness over repeated presentations (cycles) of a sawtooth amplitude modulation consisting of sudden 1.7 dB rises and eight second falls. The illusory increases in loudness were associated with the sudden transitions. These were perceptible, the slow falls were not. In the reverse condition the effect was attenuatuated. Thus rapid intensity changes separated by slow returns illicit a percept of increasing loudness.

Using more sophisticated stimuli and methods derived from the brightness illusion, Jestaedt et al (1978) elicited strong effects with larger intensity transitions at a number of frequencies. Once again rapid transitions biased the loudness percept in the direction of this change.

Rutland (1976) describes a loudness illusion over a range of frequencies from 1.25 kHz to 8 kHz. Adaptation to 8 Hz sawtooth AM produced an illusion of loudness change, in the opposite direction to the sawtooth ramps, for constant intensity test stimuli. The rapid returns of the adapting waveform had no effect, the illusion being unmodulated.

1.4.4 Other Adaptation Phenomena

Rosenblith (1947) reported that exposure to pulse trains and to a lesser extent square-waves produced a change in timbre of familiar sounds (e.g. handclap, voice) in such a way that they seemed metallic with a ringing obligatto. The effect was due to the higher harmonics of the adapting stimulus. The longer and more intense the adapting stimulus the longer the duration of the effect (the maximum was about 12 seconds). Only a limited range of pulse repetition rates were effective, ∿40-200 pps at 75 dB SPL and 30-300 pps at 85 dB SPL. A silent interval between adaptor and test reduced the effect.

Zwicker (1964) found that a tonal after-image occurred after stimulation with broad-band noise with a half-octave stop band. The after-effect corresponded in pitch to the missing region of the noise band.

Besser (1966) used interrupted noise to determine the auditory flutter fusion threshold (AFFT) defined as the rate of interruption at which the stimulus sounded continuous (about 45 Hz at 60 dB SPL). Exposure to adapting stimuli for a minute shifted the AFFT even if the adapting interruption rate was above the AFFT, i.e. the adaptor was perceived as continuous.

Using an adapting stimulus consisting of white noise added to a delayed version of itself (rippled noise), Wilson (1969) found that a complementary after-image was formed on a white-noise background. The spectral peaks of the after-image corresponded to the spectral troughs of the adapting stimulus. The findings were consistent with local adaptation at the spectral peaks of the adapting-stimulus producing a reduced response in these spectral regions during presentation of the white-noise test-stimulus.

Recently, Hall and Soderquist (1978) have examined the coding of residue-pitch using adaptation techniques. Residue-pitch channels were postulated specific for spectral region and ear of presentation.

1.4.5 Discussion

Evidence has been provided for FM specific channels (Kay and Matthews, 1972; Regan and Tansley, 1979; Gardner and Wilson, 1979; Tansley and Regan, 1980) and AM specific channels (Rutland, 1976; Regan and Tansley, 1979;

Tansley and Regan, 1980). Some moderation must be exercised in the interpretation of the results until the basis for the interaction between FM and AM found in the majority of studies is determined. Some attempts at this are made in the present study.

Evidence for directional specificity came from Gardner and Wilson (1979) and Tansley and Regan (1980) for FM channels and Rutland (1976) and Tansley and Regan (1980) for AM channels. As reported in the previous section, neurophysiological evidence exists for FM selective neurones at higher levels of the auditory system. Also, most FM responding neurones show a preference for one direction of frequency sweep, e.g. in the cochlear nucleus of the cat (Evans and Nelson, 1966; Erulkar et al, 1968) and rat (Moller, 1974), the inferior colliculus of the cat (Nelson et al, 1966; Watenabe and Ogushi, 1968) and rat (Clopton and Winfield, 1974; Vartanian, 1974), and cortex of the cat (Whitfield and Evans, 1965). For most subcortical units, this selectivity can be explained in terms of the temporal and spatial characteristics of the units lateral-inhibitory sidebands (determined by steady-state stimuli) vis-a-vis the sweep parameters (Vartanian, 1974). A possible neuronal basis for directional-specific effects thus exists.

Evidence for channels concerned with the direction of sound source movement come from Heffer (1978) and Grantham and Wightman (1979). Units have been found in the auditory cortex of the cat sensitive to precisely this (Sovijarvi and Hyvarinen, 1974).

The Rawdon-Smith illusion (Rawdon-Smith and Grindley, 1935; Jestaedt et al, 1978) is a more complicated phenomenon probably unrelated to the illusion of Rutland (1976) if only because of the time course of the sawtooth cycle. Jestaedt et al (1978) concluded that the illusion probably reflected properties common to all sensory systems.

The effects of Rosenblith (1947) and Besser (1966) are difficult to explain. The former study may involve pure-tone adaptation or TTS produced by the higher harmonies of the adapting stimuli resulting in colouration of the spectrum of the test stimuli (see Wilson, 1969).

In summary, auditory adaptation can take the form of threshold elevations or illusions. Evidence has been provided for FM specific channels organised on a directional specific basis. Tuning to carrier and modulation frequency has been demonstrated for periodic FM.

1.5 Psychoacoustical Studies of FM Stimuli

1.5.1 Introduction

A large body of literature is concerned with thresholds (dBSL), masking, just noticeable frequency deviation, pitch, etc. of FM stimuli. Because a large proportion of this literature is concerned with the perception of FM stimuli rather than FM per se only papers directly addressing the processing of FM are discussed.

Of special relevance are studies using FM to determine the frequency dL as a measure of the frequency discrimination of the ear (e.g. Shower and Biddulph, 1931). These thresholds are the same as those measured in this study and provide a useful comparison for unadapted thresholds (discussed later in Chapter 7).

1.5.2 The Coding of Frequency and Amplitude Changes

In accordance with Coninx (1978a,b) just noticeable difference (jnd) refers to steady-state stimuli and just noticeable modulation (jnm) to modulated stimuli.

Zwicker (1962) discusses a model for the detection of frequency and intensity changes based on a common detector the input of which is given by the "auditory excitation pattern", the shape of which was inferred from masking data.

The model is based on the consideration of the ear as a frequency analyser consisting of a large number of overlapping bandpass filters tuned to different frequencies over the range of audible frequencies. This concept is exhibited physiologically in the frequency tuning of single units at different levels of the auditory system (e.g. see Evans, 1975), and psychoacoustically as the critical band (see Scharf, 1970; Plomp, 1976). For critical band filters tuned to frequencies off the centre frequency of frequency transitions an amplitude-modulated output would occur as the transition crossed and recrossed the edge of the filter. Alternatively the edge of the "internal excitation pattern" could move with the transitions. FM could thus be regarded as being converted to AM, in that the neural activity elicited in some frequency-tuned channels by FM would be similar to that elicited by AM. This hypothesis suggests that FM and AM are coded by a common mechanism that takes as its input the modulation of neural activity (or shift in the edge of an excitation pattern) common to these modulations, i.e. separate channels coding FM and AM might not exist.

According to this model the detection or discrimination of combined frequency and intensity changes could be enhanced, or degraded, depending on the phase relationship between FM and AM modulating waveforms in mixed modulation signals, or the direction of frequency and intensity changes in steady-state stimuli. The critical phase relationships or direction changes would be dependent on which edge of the pattern the subject was basing his judgement, this being determined by appropriate masking stimuli.

Data suggesting a common coding model are: (a) the similarity of plots of jmn vs repetition rate for FM and AM suggesting , at threshold, FM and AM detection mechanisms have similar time functions (Zwicker, 1962); (b) examination of absolute values of jnm for tones and noise show that if they are viewed as a change in intensity of the lowest covered critical band the value of 1 dB obtained is the same as that for amplitude jnds.

Zwicker (1962), using noise bands, found that the modulation sensation for FM was increased by adding in-phase AM and decreased by adding 180° out-of-phase AM in the presence of a high-pass noise masker, i.e. when the judgement was made on the low-frequency edge of excitation pattern. This would be predicted by the common coding model described above.

Allanson and Newell (1966) used tones simultaneously modulated in frequency and amplitude to test the model. By varying the phase difference between the modulating waveforms various enhancements and cancellations reflected in the excitation pattern across an array of frequency tuned fibres could be produced. Classification of the mixed modulation signals was found to be difficult as was matching to pure FM stimuli. The matching experiments showed a bimodal distribution, i.e. S's fell into two groups according to phase angle judgements for best matches. Though hard to interpret the results showed some dependence of the subjective properties of the mixed modulation stimuli upon phase angle providing support to the common coding model.

Feth (1972) criticised this study believing that the phase dependent spectral patterns of mixed modulated stimuli could have provided the basis for S's judgements. In order to obviate this possibility Feth (1972) designed a 2 AFC discrimination experiment involving tones differing in intensity only or both frequency and intensity. The test tone always had a higher intensity than the standard. The standard in turn was of the same frequency as the test or had a higher or lower frequency increment relative to the test. Three tasks were performed by the S's: (1) simple intensity discrimination (i.e. no frequency difference between test and standard; (2) as above but with the standard at a higher frequency; (3) as above but with the standard at a lower frequency. In all cases S's had to decide whether the test was more or less intense than the standard. These tasks were carried out in the presence of either low or high-pass maskers, i.e. the S was forced to base his judgement upon only one edge of the excitation pattern. The predictions of the common coding model as to the S's performance in the three tasks in each masked condition were not met. In the low-pass condition it would be expected that S's performed best of all in task (3), where the shift in the position of the edge of the excitation pattern between test and standard would be greatest, then task (1), then task (2). The reverse order would be expected in the high-pass condition. This did not occur. Added frequency information did have an effect if it could be discriminated on its own.

Zagorski (1975) found performance in a 2IFC task with tones differing in intensity, frequency, or both, to be best when both cues were available. However, analysis of the data showed that the information was not combined, i.e. independent processing of the cues occurred. The information could be combined in the sense that both perceptual independent cues could be used in the detection or decision process.

Coninx (1978a) used a forced choice procedure to measure jnds for stimuli differing in both intensity and frequency (unlike Feth, 1972, both the intensity and frequency differences were in the test tone), and jmns for mixed FM-AM stimuli. High- and low-pass maskers were employed to ensure that one edge only of the excitation pattern was used. Jnds and jnms were plotted as contours on the frequency (ΔF) - intensity (ΔI) plane (see Fig. 1.2 for examples). A symmetrical contour represents insignificant interaction of frequency and intensity, i.e. the direction of intensity change or phase of AM relative to FM is unimportant. Asymmetrical contours represent significant interaction and would support a common coding model. At low frequencies (f_c) no significant interaction was found but asymmetries were found above 4.0 kHz. In order to determine the basis of this interaction equal loudness contours (ELC) and equal pitch contours (EPC) were determined. These contours had significant slopes at the higher frequencies such that conversion of the frequency and intensity of a stimulus into the perceptual attributes pitch and loudness at these frequencies, would show significant effects of frequency upon loudness and intensity upon pitch. The data were replotted taking this interaction into account. This had the effect of removing asymmetries at the higher frequencies. Low frequency data were unaffected because of the low slopes of the ELC and EPC at these frequencies (see Fig. 1.2). The predictions of the common coding model were not met.

Fig. 1.2: Frequency-intensity contours from Coninx (1978a).

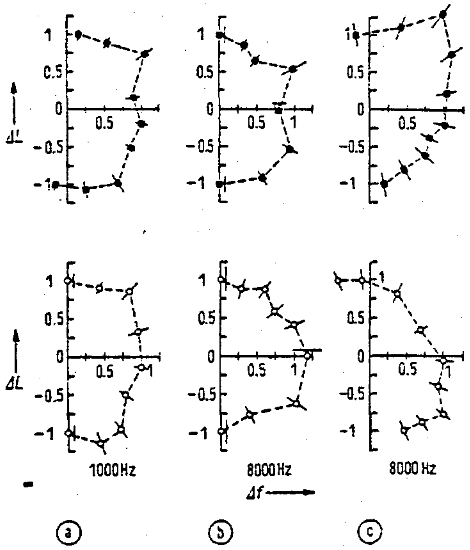


Fig. 10. Transformed jnm-contours for three stimulus conditions:

(a) partly-masked 1000 Hz pure tone (original contour in Fig. 5a),
(b) non-masked 8000 Hz pure tone (original contour in Fig. 5b),
(c) partly-masked 8000 Hz pure tone (original contour in Fig. 5c).

The scale factors are the same as for the original contours, and are given in Table II. Results for two subjects: FC (open circles) and CK (closed squares).
Bars indicate the standard deviation of the jnm's.

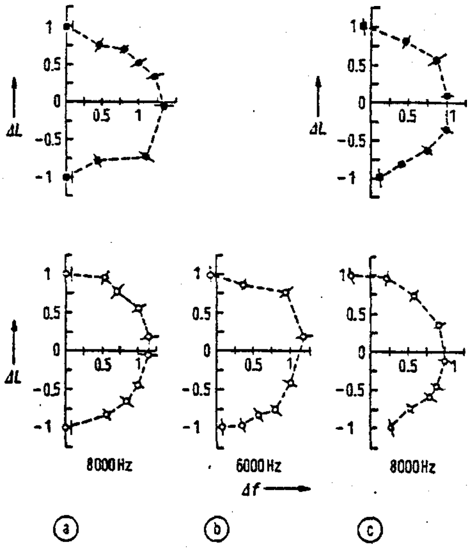


Fig. 8. Transformed jnd-contours (see text). Scale factors of the axes are equal to the scale factors of the original contours, and are given in Table I. The results of two subjects FC (open circles) and CK (closed squares) are presented for three stimulus conditions:

(a) 8000 Hz pure tone (original contour in Fig. 2c),
(b) 6000 Hz partly-masked pure tone (original contour in Fig. 3d),
(c) 8000 Hz partly-masked pure tone (original contour in Fig. 3e).

Bars indicate the standard deviation of the jnd's.

Further evidence against this model comes from Coninx (1978b) who asked Ss to adjust the depth of modulation (ΔF) of an FM tone to match that of a FM-AM stimulus with various depths of AM. The mixed stimulus modulating waveforms were either in- or 180° out-of-phase. High-pass maskers were used. The matching data showed a significant effect of phase with out-of-phase signals having the greatest modulation sensation. The effect of phase disappeared when the AM depth scale was transformed into loudness modulation by taking account of the effects of frequency upon loudness as measured by the ELC. The slope of the EPC was insignificant.

Less direct evidence against a common coding model is as follows:

(1) The frequency dl (jnd) for steady tones in a 2IFC procedure is not a constant fraction of the critical band (Moore, 1974). That the jnd is a constant fraction of the critical band is a prediction of the common coding model where the steepest slope of the excitation pattern has a constant value on a critical band scale of 27 dB/Bark. In the light of Moore's (1974) evidence the model would have to be restricted to modulated stimuli.

(2) The dl obtained with FM stimuli is consistently larger, by about a factor of two, than those found for steady-state stimuli for the same subjects and psychophysical procedure (Jestaedt and Sims, 1975; Moore, 1976; Fastl, 1978). Furthermore, Jestaedt and Sims (1975) found performance levels for FM tones to differ from steady tones as a function of frequency and paradigm. Moore (1976) found dl's for FM tones did not correlate significantly with those for steady tones in a 2IFC task and that FM data showed less scatter and more stability. Thus suggests FM detection involves different mechanisms than the detection of frequency differences between steady tones.

(3) The psychophysical paradigm is of critical importance with differences in dl between paradigms of factors of 2 to 4 for both FM and steady tones (Jestaedt and Sims, 1975; Wier et al., 1976; Fastl, 1978). These differences probably reflect the different decision and detection

processes required by the tasks including memory factors in discrimination tasks (Jestaedt and Sims, 1975).

(4) Moore (1973a,b) found frequency dL's for short duration tones and narrow bands of noise to be consistent with a place model involving fluctuating excitation patterns (common coding model) above about 4 kHz. Below this value, however, dL's were consistent with a temporal mechanism.

(5) Fastl (1978) found large individual differences in dL of up to a factor of 27.

The dependence of frequency dL's upon stimulus, paradigm and frequency provide evidence against the simple model discussed earlier and suggest the perceptual mechanisms involved are task dependent. Together with evidence directly addressing the question of the common coding of frequency and amplitude changes, including adaptation data, it must be concluded that such a model is untenable. The existence of a common (peripheral) component in the ears response to FM and AM does not imply a common coding mechanism. Frequency and amplitude changes can be combined as perceptually independent cues at a detection stage (Zagorski, 1975) consistent with the model of Regan and Tansley (1979) and Tansley and Regan (1980).

As a final point, if, as the data discussed earlier suggests, modulation detection involves different perceptual processes to the detection of steady-state frequency differences, then the use of steady-state data to support assumptions about FM processing (as in Feth, 1972; Zagorski, 1975; and some experiments of Coninx, 1978a) can be called into question.

1.5.3 A Spectral Basis For FM Detection?

Feth et al (1969) examined periodic FM detection by a method of adjustment for sinusoidal and triangular FM as a function of modulating frequency. The authors determined the real spectra of their signals and compared them to the ideal, calculated spectra. Differences thus obtained were used to calculate a correction factor for conversion of detection data to frequency dL. Contrary to the classic results of Shower and Biddulph (1931) the dL did not increase from modulating frequencies from 1 to 16 Hz but remained constant. A number of problems exist however in contemplating a spectral basis for FM detection. At low values of f_m the ear does not integrate the stimulus signal for a long enough time to create a valid representation of the spectrum and consequent resolution of spectral peaks upon which detection would be based. Second, Feth et al (1968) determined spectra at modulation depths above detection levels where they might be expected to be different (Hartmann and Klein, 1980).

Hartmann and Klein (1980) discuss two modes of FM detection, one, at low modulating frequencies, based upon temporal factors, and the other, at values of f_m approaching the critical band, based upon spectral factors (Zwicker, 1952 reported in Plomp, 1976). Above or near the critical bandwidth spectral peaks can be resolved.

Evidence from adaptation experiments, essentially FM detection experiments, show that there is no spectral basis to threshold elevation (Kay and Matthews, 1972; Regan and Tansley, 1979) and, therefore, no spectral basis for FM detection at the modulation frequencies used in the studies(8 Hz and 2 Hz respectively). Further, the tuning to modulation frequency reported by Kay and Matthews (1972) shows the importance of temporal factors in detection and adaptation.

Terhardt (1974) has shown that the perception of periodic sound fluctuations, the sensation of roughness, for FM and AM stimuli to be determined primarily by fluctuations in relative amplitude of the sound envelope within bandwidths defined by the critical band.

1.6 Relationship of Selective Adaptation to Masking - Auditory, Fatigue and Adaptation

An important question is the relationship between selective adaptation and other auditory phenomena involving changes in sensitivity specifically masking, fatigue and adaptation. The main difference is the threshold measured. The determination of minimal detectable frequency deviation in supra-threshold stimuli is the basis of FM adaptation studies. Masking and the other measures involve measurement of sensation level thresholds, or in the case of adaptation, loudness change. Both fatigue and adaptation can be dismissed in that measurable sensitivity changes require stimuli much louder than those of the present study (45 dBSL) and the time course of recovery is of a different order to that of FM adaptation (Moore, 1977).

The most direct evidence against the role of masking in FM adaptation is the feature specificity, accepted with certain reservations, of the adaptation, as discussed in section 1.4.1, and the independence of adaptation from spectral factors. Thus, though AM or quasi-FM might be capable of masking an FM stimuli given the necessary spectral and temporal conditions, no elevation of FM thresholds occurs. The same can be assumed in the case of FM tests and adaptors that though FM threshold elevation can occur this does not have a spectral basis, though masking might occur. Further, the time course of masking is of a different order to those determined by Kay and Matthews (1972) for the decay of FM adaptation. The decay of masking is rapid, often within 100 ms (Elliot, 1971). Masking is largely independent of masker duration after 20 ms. This is not the case for FM adaptation where adaptation increases with increasing adapting durations of the order of tens of seconds.

Masking is discussed later in the experimental chapters.

1.7 Speech Adaptation Experiments

1.7.1 Introduction

The need to explain the phenomenon of categorical perception led to the use of selective adaptation as an approach to the understanding of speech perception. In categorical perception members of a series of speech sounds are assigned to one of two categories, the point in the series at which the change from one category to the other occurs is the identification boundary. The categories are phonetic, for example, place of articulation and the voiced-voiceless distinction; the series however contains a gradual change in the acoustic properties acting as cues to the phonetic properties. The phenomenon is one of identification or labelling.

The basic paradigm of speech adaptation involves the presentation of rapidly repeated synthetic syllables, usually of consonant-vowel format, e.g. /ba/-/da/, from a speech series with a categorical identification function. Adaptation with end-point stimuli, that is, those at the extremes of the series, results in a shift of the category boundary towards the adapting stimulus: more stimuli are assigned to the opposite category.

The first models (Eimas + Corbit, 1973) forwarded to explain this phenomenon were typical neurophysiologically based feature analysis models. The speech analysis system was assumed to consist of a hierarchy of increasingly complex and selective phonetic analysers, often organised as opponent process detectors. These analysers were assumed to be "fatigueable" through adaptation and the selectivity of this "fatigue" in shifting category boundaries considered evidence for opponent process detectors where appropriate. Such detectors could also provide the basis for non-adapted categorical perception. This model was largely derived from models of visual information processing for visual motion and colour. The inadequacy of this model was revealed by later studies, leading to models of increasing complexity including auditory feature analysers.

The first studies positing a simple opponent process phonetic model were Eimas and Corbit (1973) and Eimas, Cooper and Corbit (1973). These authors demonstrated adaptation for the voiced-voiceless continuum. The effects transferred interaurally implying a central location for the mechanism of adaptation. An auditory basis for the effect was ruled out by the finding that non-speech stimuli consisting of the initial segment of the synthetic speech sound did not produce adaptation. However, evidence against a purely phonetic or linguistic model was not long in coming. Bailey (1973) used synthetic C-V stimuli cued by formant transitions (evidence, incidently, for the role of frequency transitions in speech perception) to produce a 10-point series of /ba/ to /da/ and also /bΣ/ to /dΣ/ corresponding to place of articulation. This phonetic feature has an advantage over the voiced/voiceless distinction in having a limited number of acoustic cues. Adaptation as described by Eimas and Corbit (1973) occurred but was contingent upon the spectral overlap of the adaptors and the test series. When place of articulation cues were carried in different formants for test and adapting stimuli little adaptation occurred. The role of spectral information was confirmed by Bailey (1974). When the spectral separation between the adapting stimuli and the test series was large, adaptation effects were reduced or non-existent.

Since these early papers a large body of literature has been produced dealing with adaptation in general and linguistic versus auditory detector models specifically. Some of this work is dealt with below. The discussion is brief because the work does not have a significant bearing on this study. Also the phenomenon of speech adaptation is itself in doubt (Simon and Studdert-Kennedy, 1978; Remez, 1980) as are simple hierarchical and serial processing models (Wood, 1974; Repp, 1977).

1.7.2 Literature Review

Ades (1974) using a place of articulation continuum studied the role of acoustic features in adaptation including that of formant transitions. In experiments designed to distinguish between phonetic and acoustic based adaptation the predictions of the [illegible] model were largely met. Acoustic cues did have some influence, adaptation being greater when both test and adapting stimuli had falling F3 transitions. Adaptation was found to be contingent upon consonant position in a syllable, i.e. upon linguistic context. Diehl (1975) with a place of articulation series used end-point adaptors as well as these adaptors with the formant transitions replaced by noise bursts. Also used were syllables having the same place of articulation but different consonants. All adaptors shifted the category boundary. This suggested a phonetic basis to adaptation with place of articulation the critical variable independent of the actual consonant or auditory properties of the adaptor compared to the test series. Ganong (1975, 1978) carried out similar experiments with a place of articulation series. He too found that consonant differences had no effect as long as place of articulation was the same as the end-point stimuli. If, however, the consonant difference was combined with a change in acoustic properties, namely, a substitution of noise-bursts for transitions a reduced effect was found. Though this seems to support an auditory theory the phonetic theory could accommodate the noise-burst result by assuming transitionless adaptors were "weak" phonetically. This was confirmed by the subjects reports. An auditory theory would require a widening of the range of acoustic cues for place of articulation beyond simple transitions involving mechanisms sensitive to bursts and transitions.

Tartter and Eimas (1975) used a place of articulation series with either complete end-point adaptors, transitionless adaptors (F1, F2 or both) and chirps consisting of 45 ms of all transitions. All stimuli produced some boundary shift though the effect was greatest for the complete stimulus. Adding the missing portions of the adaptors resulted in increased adaptation even if these portions were not specifically cues for place of articulation. Similar results were found for the voiced/voiceless continuum in direct contrast with the finding of Eimas et al (1973) that chirps were ineffective. Though suggesting an auditory analysis it is possible that overall similarity acoustically and phonetically is required for the greatest effects, i.e. that a linguistically based effect is contingent upon acoustic information. This would not explain the effect of non-speech chirps however.

Pisoni and Tash (1975) found adaptation of a CV series by non-speech VC adaptors supporting an auditory model and in direct contrast to the finding of Ades (1974) that the effects were contingent upon linguistic context.

Sawusch (1976) presented evidence against a simple opponent-process model by using a rating paradigm instead of a two category decision. This revealed adaptation at all points on the side of the adapting stimulus and not just at the category boundary. Points on the opposite side showed no change in rating. Sawusch (1977) replicated the effects of Ades (1974) on the role of vowel context. Even with complete spectral overlap of F2 and F3 no effect of VC upon CV syllables, and vice versa, was found. Further evidence for a linguistic basis was supplied by the finding that only VC-like and not vowel or vowel-like adaptors shifted the boundary for CV stimuli. This might of course reflect an incomplete acoustic specification as in the reduced adaptation found by Tartter and Eimas (1975) for incomplete adaptors.

1.7.3 Problems and Discussion

It can be seen from the above review that speech adaptation data is often conflicting and unclear as to the validity of phonetic as opposed to auditory models if, in fact, such a distinction is itself valid. What is clear is that adaptation effects are contingent upon the acoustic properties of the stimulus (Bailey, 1973; 1974; Ganong, 1975; 1978; Tartter and Eimas, 1975; Pisoni and Tash, 1975). It would seem that acoustic cues and auditory processing have some role in the identification of speech sounds, indeed it would be strange if they did not. The question of whether speech adaptation is the adaptation of auditory feature analysers has hardly been touched, though some studies do suggest this is the case (e.g. Tartter and Eimas, 1975; Pisoni and Tash, 1975).

One danger of looking for an auditory basis of distinctive feature processing (a phonological concept) is that many acoustic cues control the distinctive features of speech sounds (Parker, 1977). In the search for an acoustical basis for speech adaptation the demands made of the auditory feature analysis system become increasingly elaborate. Cues to phonetic structure are highly variable and distributed dynamically across an entire syllable. This does not conform to the demands of a feature analysis system segmenting the speech signal into a set of invariant properties. The increase in the complexity of feature analysis models whether phonetic or phonetic/auditory can be followed in the literature from the first paper of Eimas and Corbit (1973). The use of physiological models of the opponent-process type, not restricted to phonetic models, are doubtful when considering the complex variables that form the acoustical basis of speech sounds. Further, little attempt has been made to equate speech and auditory adaptation experiments (e.g. Kay and Matthews, 1972). Speech adaptation has concentrated on measuring shifts in identification or labelling rather than sensitivity changes.

Of more fundamental importance is the recent finding of Simon and Studdert-Kennedy (1978) that speech adaptation is indistinguishable from the phenomenon of stimulus anchoring. The authors discuss the procedural differences between speech adaptation (measured as category assignment) and anchoring. In adaptation the adaptor occurs many times, with short inter-stimulus interval (ISI), in a single block before the test stimuli series of which it is part. In anchoring the anchor occurs less frequently, with longer ISI, and is scattered randomly among the test series. The main difference between the procedures is the number and distribution of adaptor and anchor stimuli. Variations in fundamental frequency, intensity and vowel were introduced into a place of articulation series, i.e. on a particular series one of these properties would covary with place of articulation. In adaptation judgements based on pitch or loudness are dissociated from those based on the phonetic feature. Selective adaptation and category judgements of non-phonetic continua are possible, itself evidence against the premise of specialized detectors for categorical perception. This was true also of anchoring. By making the two procedures as comparable as possible in the distribution of adaptor/anchor energy the two phenomena could be compared. Differences in the shift in category boundaries in stop consonant series (place of articulation) were a matter of degree only reflecting the anchor concentration, making "fatigue" less likely in these conditions. Anchoring was as selective as adaptation. Anchoring is usually seen as a phenomenon resulting in a shift in the psychological midpoint of a stimulus series following presentation of an end-point anchor. The distribution of the subjects response is thus shifted. The authors discuss other psychophysical processes and their relation to anchoring/adaptation.

Remez (1980) has found adaptation on a speech-non-speech continuum. Non-speech sounds were buzzes having neither phonetic nor acoustic properties in common with the speech end of the continuum. Both speech and non-speech adaptors produced boundary shifts. Obviously neither a phonetic nor acoustic feature analysis could account for this unless the system is so plastic the subject can construct the necessary feature analysis for the task. The results imply that speech adaptation does not involve the "fatigue" of specific detectors, be they phonetic or acoustic. Other psychological processes must underly the phenomenon.

Burns and Ward (1978) have produced evidence of categorical perception for musical intervals having no natural categories or boundaries when procedures equivalent to those of speech category experiments were used. This involved the use of series differing by equal increments along relevant dimensions. When variable increments were introduced categorical perception was abolished. The phenomenon would thus seem to be related to procedure and stimulus uncertainty. Once again this suggests a role for central psychological factors in speech adaptation and not simply adaptation or "fatigue" of tuned feature detectors.

CHAPTER 2: METHODS

2.1 Procedure

The experiments reported in this study involved the determination of thresholds for the detection of frequency-modulation defined in terms of the extent of frequency excursion of the FM in Hz (see Fig. 2.2). Both unadapted thresholds, which were stable over time, and adapted thresholds, which decreased (decayed) over time (see Kay and Matthews, 1972) were measured.

Thresholds were measured with a two interval forced choice (2IFC) procedure (examples are shown in Fig. 2.1). One cycle of the procedure consisted of a five second adaptation signal (this was true for all experiments but one) followed by two test intervals. All signals were separated by silent gaps. The durations of the test intervals and all silent gaps were dependent upon the experiment conditions and are reported in the method sections of specific experiments. The upper and lower limits of the test interval duration were 1 second and 62.5 ms respectively.

In each test pair one interval contained an FM stimulus, the other an unmodulated (pure-tone) stimulus. The order of presentation was randomised on each trial. The subjects task was to choose which interval contained the FM stimulus and to respond during the next adaptation interval. Response error feedback was provided. The carrier or centre frequency (f_c) (see Fig. 2.2) of the FM test stimulus was always equal to the frequency of the pure-tone test stimulus.

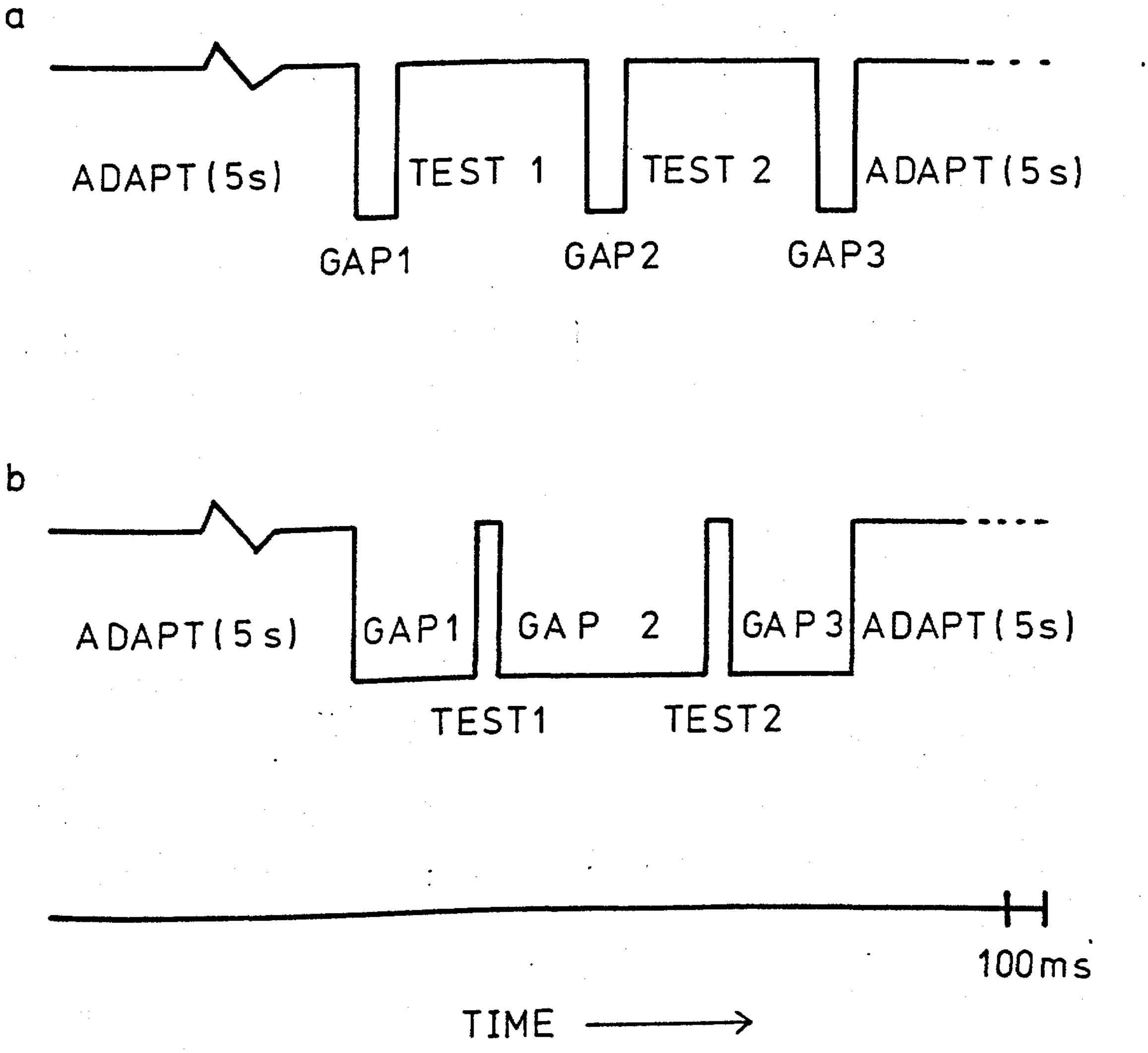
The frequency excursion of the FM test stimulus was randomly selected on each trial from four possible values and used to plot the psychomatic function. The frequency excursion giving 76% correct response was taken as threshold. A single threshold determination was based on a sequence of a 100 or more cycles (trials), i.e. about 25 decisions for each of the four test levels, for a particular stimulus condition. Two or three

Figure 2.1: Time diagrams showing examples of 2IFC cycles. All adaptation intervals (ADAPT) of 5s duration.

(a) Test intervals of 500 ms duration, gaps of 100 ms (see Section 3.1.2).

(b) Test intervals of 62.5 ms duration, gaps 1 and 3 of 319 ms and gap 2 of 537.5 ms duration (see Section 3.3.2).

Test intervals and gaps drawn to scale.


a
ADAPT(5s)
TEST 1
TEST 2
ADAPT(5s)
GAP1
GAP2
GAP3
b
ADAPT(5s)
GAP1
GAP 2
GAP3
ADAPT(5s)
TEST1
TEST2
100ms
TIME

threshold determinations were carried out for each stimulus condition. The time between the threshold determinations within a single stimulus condition was three to five minutes. The time between threshold determinations for different stimulus conditions was usually longer than ten minutes. The possibility that adaptation might have persisted in the interval between threshold determinations is discussed in Appendix B.

S's were seated in a sound-proofed booth providing about 45 dB attenuation in a quiet laboratory, for all experiments.

The UNADAPTED (REFERENCE) THRESHOLD was that determined when the adaptation interval contained a pure-tone stimulus with a frequency equal to that of the test stimuli. Other adaptation interval stimuli are referred to as ADAPTING STIMULI and the threshold determined with these stimuli as the ADAPTED THRESHOLD whether or not adaptation actually occurred.

Threshold elevation (or facilitation) is expressed as the ADAPTATION FACTOR defined as

$$\frac{\text{ADAPTED THRESHOLD}}{\text{UNADAPTED (REFERENCE) THRESHOLD}}$$

Thus, when the value of this term is 1 no adaptation has occurred, when greater than 1, threshold elevation (adaptation) has occurred, and when less than 1, threshold facilitation (sensitisation) has occurred.

The duration of the adaptation (5 seconds) was chosen after consideration of the results of Kay and Matthews (1972). They found that following adaptation to a 12s tone sinusoidally frequency-modulated around 250 Hz at a rate of 8 Hz, the detection threshold (in terms of frequency excursion) for a sinusoidal FM tone (with the same carrier frequency and modulation frequency) was elevated by a mean factor of 3. Their thresholds were measured with a single interval forced-choice (YES/NO) procedure. This elevated threshold decayed exponentially, after the offset of the adaptation interval, with a time constant of 19 seconds to near zero in one minute. They also found that the size of the effect, measured with the test stimulus just following the offset of the adaptation interval, was a function of the duration of the adaptation interval. The adaptation increased with increasing duration up to about 12 seconds, adaptation remaining constant at longer durations. It was hoped that the duration of the adaptation interval of the present study was long enough to ensure that adaptation reached a maximum within the first few cycles (trials) of a threshold determination. It was also hoped that subsequent adaptation intervals would maintain a constant level of adaptation with fluctuations only occurring as the threshold decayed in the interval between adaptation intervals. This decay would be counteracted by the next adaptation interval. As will be seen in the experimental chapters the procedure did yield consistent values of elevated (adapted) threshold with acceptable standard deviations.

Another factor in the choice of the adaptation interval duration was the need to avoid long test cycle times and the possibility of subject fatigue, boredom, etc. For a duration of 5 seconds estimates took about 10.5 minutes.

Another possibility raised by consideration of the decay of threshold reported by Kay and Matthews (1972) was that of the threshold decreasing between the presentation of the two test intervals leading to a lower threshold at the second interval than at the first. It is possible that two separate thresholds were measured by the 2IFC procedure under conditions of adaptation. A further complication is that of the threshold decaying within the test interval itself, especially for longer durations of test interval. It was felt, however, that these differences would be small and could be ignored because the maximum periods between adaptation intervals in any experiment was only 2.3 seconds and between test interval onsets was 1.1 seconds. For most experiments these values were 1.3 seconds and 0.6 seconds respectively. It is interesting to note however that Kay and Matthews (1972) used test stimuli of 5 seconds duration. From their decay data one might expect appreciable decay within this period especially just after the offset of the adaptation interval. One might assume an increasing detectability of FM during the course of the test stimulus with the S basing his/her decision upon the final segment of the stimulus. This possibility would require adjustment of data describing the functions for the decay of threshold and the increase in adaptation with increasing duration of adaptation in Kay and Matthews (1972).

2.2 Subjects

Two S's participated in the study. RBG, the author, was aged 21-24 years during the period of the experiments. VJG was aged between 20-22 years during the experiments in which she participated. Both S's had audiometrically normal hearing and were aware of the nature and theory of the experiments.

2.2 Stimuli

Frequency-modulation is the process of varying the frequency of a carrier waveform in proportion to a modulating waveform. The rate of modulation or modulation frequency (F_m) of a periodic FM stimulus is equal to the frequency of the modulating waveform. The frequency deviation (ΔF) is determined by the voltage level of the modulating waveform.

Figure 2.2 serves to illustrate and define the terminology used to describe FM stimuli in the present study. Carrier waveforms were always sinusoidal.

As stated above, thresholds are defined in terms of the maximum frequency excursion, i.e. peak to peak excursion is ΔF, or as percentage modulation ($100 \pm \Delta F/F_c$). All frequency excursions were symmetrical around F_c.

Stimuli were band-pass filtered (Barr and Stroud, EF2). The values of the low and high frequency cut-off was set so as to ensure less than 1% amplitude-modulation (AM) of the FM signals. These values are shown in Table 2.1. For a few very large values of frequency excursion some AM greater than 1% but less than 2% was unavoidable.

All stimuli were presented diotically through Sennheiser HD 414 headphones at a level of 45 dBSL in a pure-tone of frequency F_c. The headphone frequency response was determined with a Bruel and Kjaer artificial ear Type 4153. The value of F_c chosen for the present study were those around which the response was flat to ±0.1 dB over the range of frequency excursions used. These values are 0.25, 0.5, 1.0 and 4.5 kHz. This ensured insignificant AM of the signal before the ear.

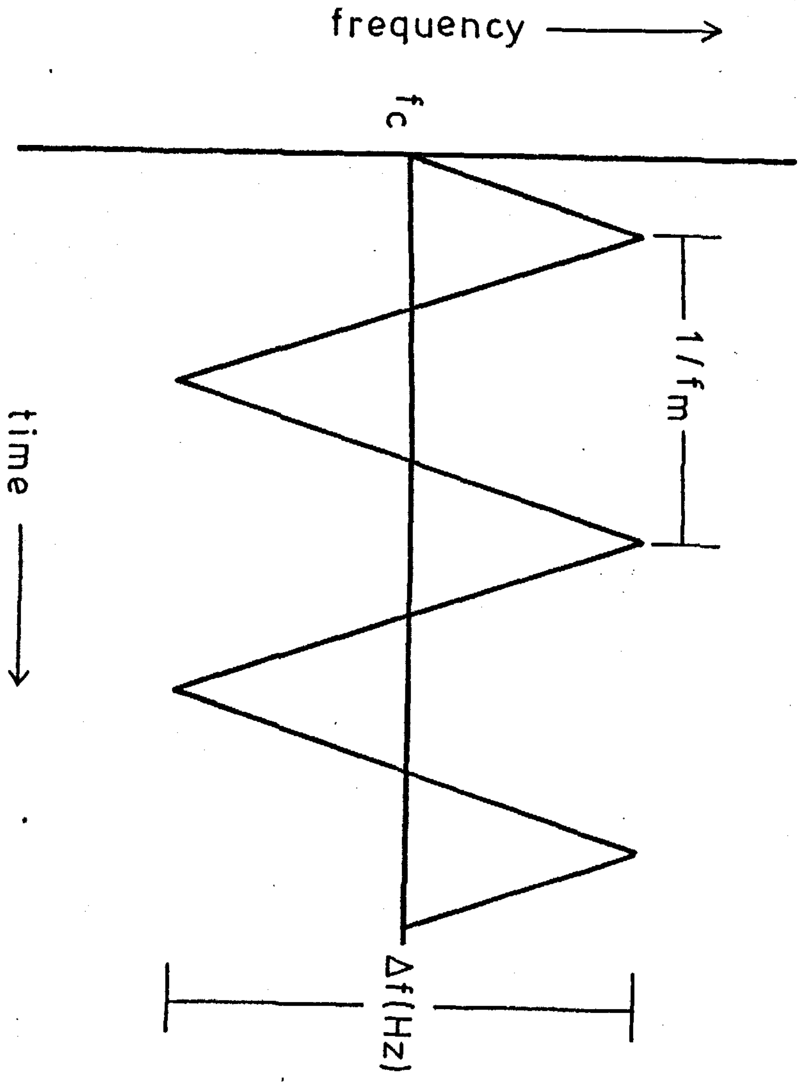
All stimulus gating functions had rise/fall times of 6 ms.

As stated above stimuli were presented at a level of 45 dBSL. This level was chosen to minimise any masking effects that might occur before different intervals. The duration of the silent gaps between intervals (never less than 100 ms) would also ensure minimal masking effects between

Figure 2.2: Frequency-time plot showing the frequency of a carrier waveform modulated by a triangular waveform of period $1/F_m$ where F_m is the modulation frequency in Hz.

ΔF *(or* $2 \times (\pm \Delta F)$*) is the extent of frequency variation* (in Hz) *around* the carrier or centre frequency F_c (expressed in kHz in this study).

The frequency variations in this study are always symmetrical around F_c.


frequency
f_c
1/f_m
time
Δf(Hz)

intervals in that most backward and forward masking would have decayed over the period of the gaps (see Elliott, 1971). One might assume that masking is unimportant in the present study in that we are concerned not with the detection of the stimuli but of the FM. However, masking within FM test intervals, i.e. the effect of one portion of the test stimulus upon preceding and subsequent portions, especially for single sweep test stimuli (see Chapter 6), may be important.

2.3 Apparatus

A block diagram of the apparatus is shown in Fig. 2.3. The essentials of this system are the generation of the gated modulating waveforms and the gating of the modulated carriers to produce the temporal pattern of the 2IFC procedure.

2.3.1 Key to Test Stimulus Modulating Waveforms and Generators

1.	Sinusoidal	Wavetek VCG Model III or Levell transistor RC oscillator Type TG150D.
2.	Triangular	Wavetek VCG Model III.
3.	Sawtooth	See below.
4.	Single linear sweeps	Purpose built triggered sweep generator.

A d.c. balancing circuit (top left of Fig. 2.3) ensured the frequency deviation was symmetrical around f_c. Another circuit (top right of Fig. 2.3) allowed adjustment of the value of f_c of the test stimuli.

2.3.2 Key to Adapting Stimulus Modulating Waveforms and Generators

1.	Sinusoidal	Levell TG150D or Advance low distortion oscillator SG68.
2.	Repetitive sweeps	Purpose built generator.
	One cycle of the waveform consisted of a linear voltage sweep followed by a constant voltage plateau, the durations of which could be independently varied (see Fig. 2.4). Down sweeps were produced by an inverting circuit.	
3.	Sawtooth	Produced by the repetitive sweep generator with tp = 0 ms. In fact the lower limit of tp was about 1.8 ms. Some loss of linearity also occurred.

The repetitive sweep generator also produced square-wave waveforms of the same frequency as the sweeps. These were used, in conjunction with the repetitive sweep adapting stimulus, as gate voltages for the FET gate system (see Fig. 2.3) discussed in more detail later. The function of

Figure 2.3: Block diagram of apparatus. Key in text.

Thick black lines represent signal paths, thin black lines represent 2IFC-cycle timer-pulse paths.

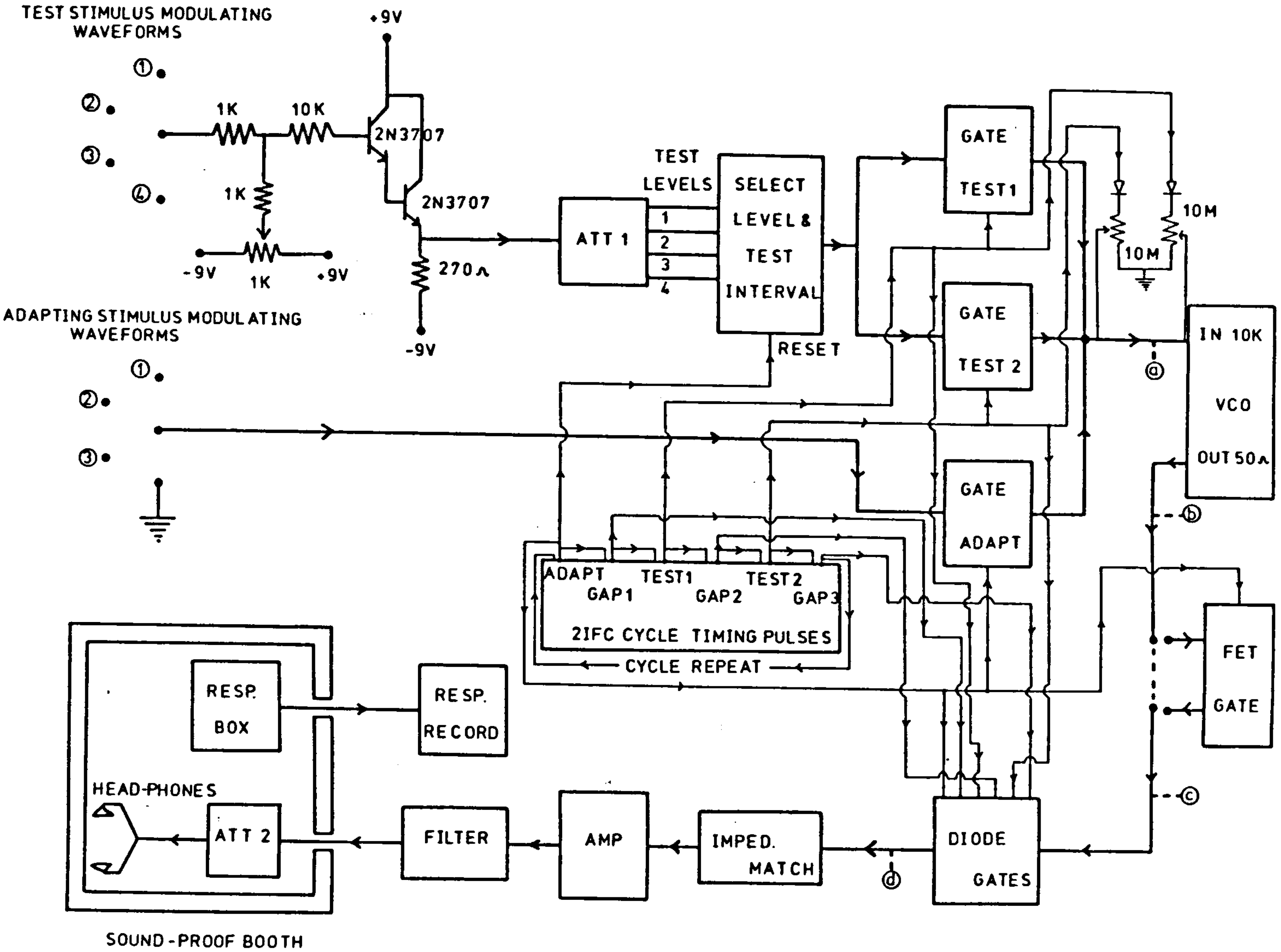
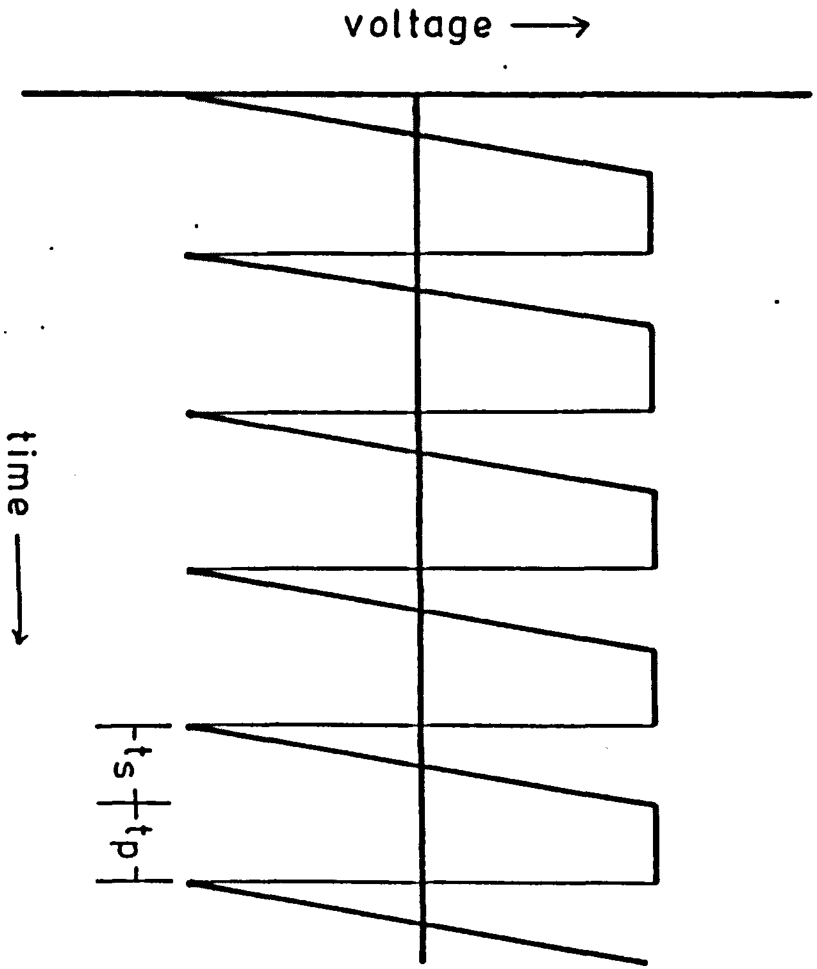

TEST STIMULUS MODULATING WAVEFORMS
①
②
③
④
1K
10K
1K
1K
-9V
+9V
+9V
2N3707
2N3707
270Ω
-9V
ADAPTING STIMULUS MODULATING WAVEFORMS
①
②
③
ATT 1
TEST LEVELS
1
2
3
4
SELECT LEVEL & TEST INTERVAL
RESET
GATE TEST1
GATE TEST 2
GATE ADAPT
10M
10M
IN 10K
VCO
OUT 50Ω
ⓐ
ⓑ
ⓒ
ⓓ
FET GATE
ADAPT
GAP1
TEST1
GAP2
TEST2
GAP3
2IFC CYCLE TIMING PULSES
CYCLE REPEAT
RESP. BOX
RESP. RECORD
HEAD-PHONES
ATT 2
FILTER
AMP
IMPED. MATCH
DIODE GATES
SOUND-PROOF BOOTH

Figure 2.4: Modulating waveform of the repetitive sweep adapting stimulus. t_s is the sweep duration, t_p the plateau duration. t_s and t_p can be varied independently.

The time between plateau offset and sweep onset is less than 1 μs.


voltage →
time →
t_s
t_p

this system was to remove the voltage plateau producing sweeps separated by silent gaps. Sawtooth modulation was also used as an adapting stimulus in later experiments.

2.3.3 Key to Signals

(a) Gated modulating waveforms - in all cycles one test interval only is modulated. The temporal pattern of 2IFC can be seen at this point.

(b) Sinusoidal carrier modulated by gated modulation waveforms of (a).

(c) As in (b) if FET gate not in use. If in use the adaptation stimulus is square-wave gated to produce tone-bursts separated by silent gaps. Tone-bursts may or may not have frequency sweeps.

(d) Modulated carrier gated to produce silent gaps in 2IFC cycle.

2.3.4 Key to Block Diagrams

ATTI - Purpose-built attenuator from which the four voltage (TEST LEVELS) levels of the test stimulus modulating waveform are derived.

2IFC CYCLE TIMING PULSES - Pulses set to the duration and order of the 2IFC cycle intervals and gaps. Used to control the duration of modulating waveforms - GATES, TEST 1, TEST 2 and ADAPT - and the DIODE GATES and FET GATE. In the latter case, it is used to ensure the gate voltages are present during the adaptation interval only. Used to ensure d.c. bias is present during test phases only. Each pulse is triggered by the proceeding pulse allowing free-running of the cycles.

VCO - Hewlett-Packard 3310A voltage controlled oscillator for generation of FM stimuli.

FET GATE - Used to square-wave-gate the adaptation stimulus under control of the adaptation interval timer pulse (ADAPT) (Fig. 2.5a). Two modes of operation exist. In the first mode the carrier is modulated by the repetitive sweep adapting stimulus giving the frequency-time plots of Fig. 2.5b. After gating by the FET gate, voltages of Figs. 2.5c and 2.5d the carrier consists of frequency sweeps separated by silent gaps (Fig. 2.5e). The gate 1 voltage swings +2V to -7V, gate 2, 0V to -9V. In the second mode, the carrier is unmodulated and gated as above resulting in tone-burst stimuli.

DIODE GATES - Produces silent gaps between intervals. Controlled by timer pulses.

IMPED MATCH - Impedence matching.

AMP - Amplifier.

FILTER - Barr and Stroud variable filter type EF2 in band-pass mode. Insertion loss as the upper cut-off/lower cut-off approcches one is b ± 1.0 dB. Attenuation response similar to that of a 6th order Butterworth function in 3b dB/oct.

ATT2 - Advance A64A step attenuator controlling stimulus level.

HEADPHONES - Sennheiser HD414.

RESP BOX - Response box incorporating light, signalling occurrence and duration of 2IFC cycle events, lever for voting and lights for feed-back of response errors.

RESP RECORD - Records responses correct and errors at each of the four test levels, total responses and therefore total number of 2IFC cycles presented.

All stimulus gating functions had rise/fall times of ∿5ms. Stimulus monitoring and calibration was done with a Tektronix dual-beam oscilloscope Type 502 and a frequency counter.

Figure 2.5: (a) Circuit diagram of FET gate system using 2N3819 devices.

(b) Frequency-time plot of inputs to FETs consisting of a carrier modulated by repetitive sweep waveform.

(c) Gate voltage of FET1 swinging + 2v → -7v.

(d) Gate voltage of FET2 inverted version of (c) swinging 0v → -9v.

(e) Frequency-time plot of the outputs of the FET system consisting of linear frequency sweeps separated by silent gaps.

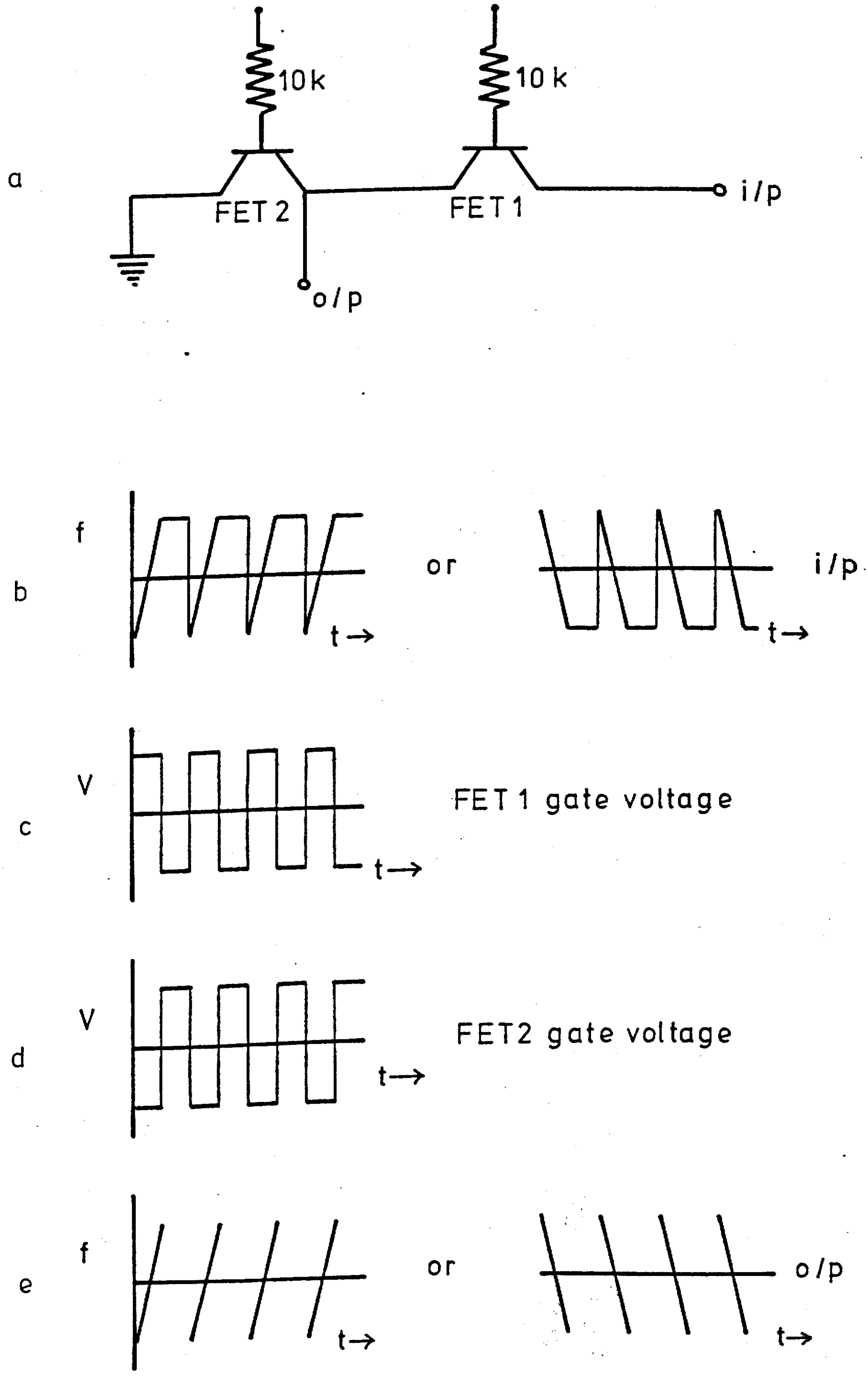

a
10k
10 k
FET 2
FET 1
i/p
o/p
b
f
t→
or
i/p
t→
c
V
FET 1 gate voltage
t→
d
V
FET2 gate voltage
t→
e
f
t→
or
o/p
t→

TABLE 2.1

Values of the high and low frequency cut-offs of the filter pass band for the 4 values of f_c

F_c (kHz)	Low (kHz)	High (kHz)
0.25	0.15	0.35
0.5	0.3	0.7
1.0	0.46	1.5
4.5	3.6	5.5

CHAPTER 3

3.1 Adaptation as a function of adapting-stimulus frequency-deviation

3.1.1 Introduction

Experiments with FM adaptation have shown the dependence of threshold elevation upon adapting stimulus duration (Kay and Matthews, 1972). The dependence of threshold elevation upon the frequency-deviation of the adapting-stimulus (±ΔF) has only recently been studied (Regan and Tansley, 1979). At modulation-frequencies of 8 Hz and 2 Hz threshold elevation increased with increasing frequency-deviation at 0.5 kHz. The resultant function was roughly linear. Similar experiments are reported here extending beyond those of Regan and Tansley (1979) at a number of frequencies.

3.1.2 Procedures

The procedure is that described in Chapter 2, i.e. repeated presentation of 5s adaptation and 0.5s test intervals separated by silent gaps. Test and adapting modulation was sinusoidal with a frequency of 8 Hz. Unadapted thresholds were determined at 0.25, 0.5, 1.0 and 4.5 kHz. The elevation (adaptation) of these thresholds as a function of adapting ±ΔF was determined at all frequencies for RBG and at 1.0 kHz for VJG. Except for 0.25 kHz three threshold estimates were made for each value of adapting ±ΔF and the mean determined. At 0.25 kHz six threshold estimates were made for values of ±ΔF up to and including ±50 Hz after which three estimates were made.

3.1.3 Results and discussion

Plots of adaptation versus ±ΔF (and percentage modulation) are shown in Figures 3.1a-d. Data points are the mean of 3 (or 6 at 0.25 kHz) threshold estimates. Vertical bars are standard deviations. Except for 4.5 kHz

Fig. 3.1a-e. Plots of adaptation factor as a function of adapting frequency-deviation (±Δf) expressed in Hz, and percentage modulation (±Δf/f_c%). Data points are the means of three threshold estimates, vertical bars are ±1 standard deviation.

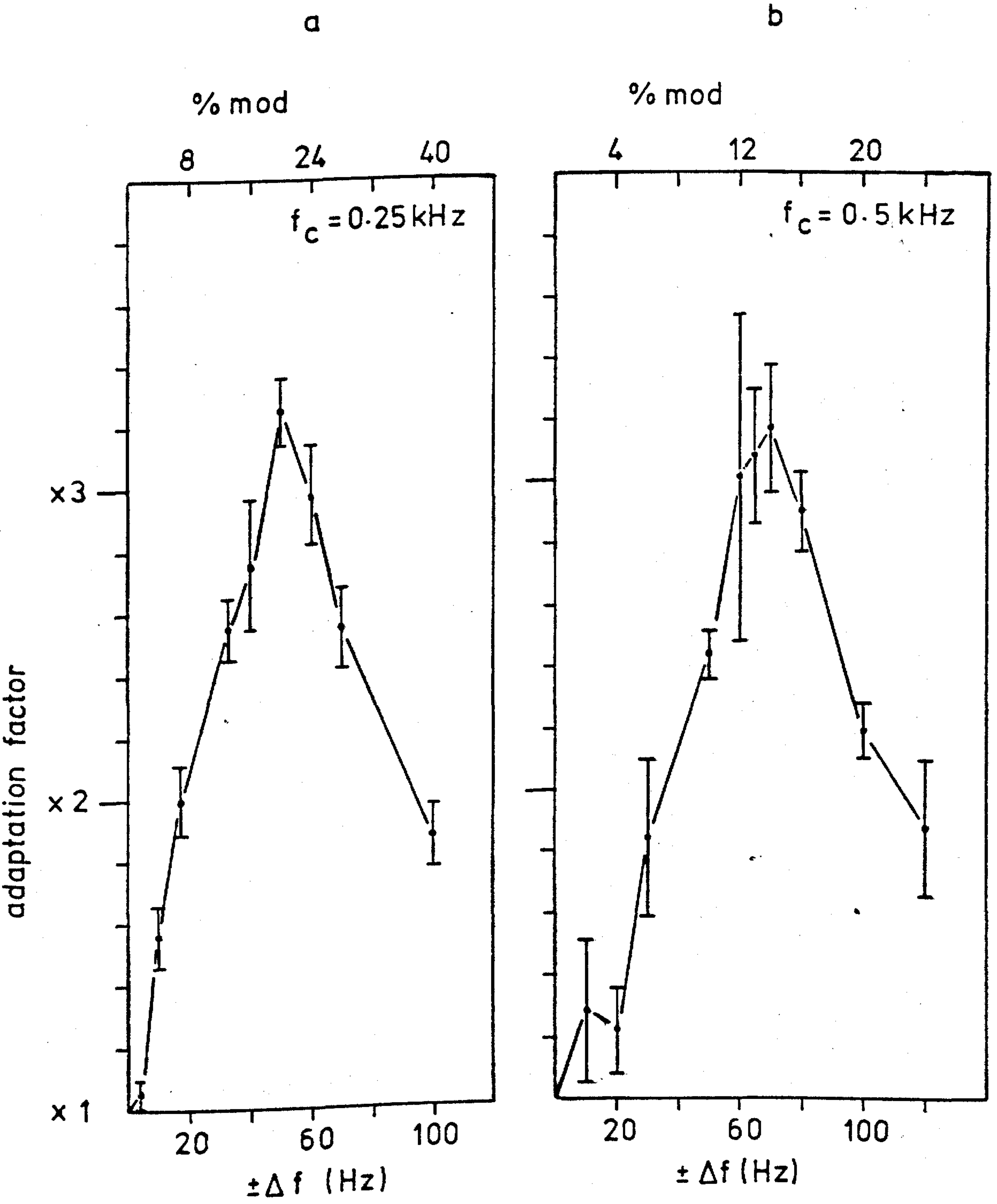
(a) f_c = 0.25 kHz, RBG

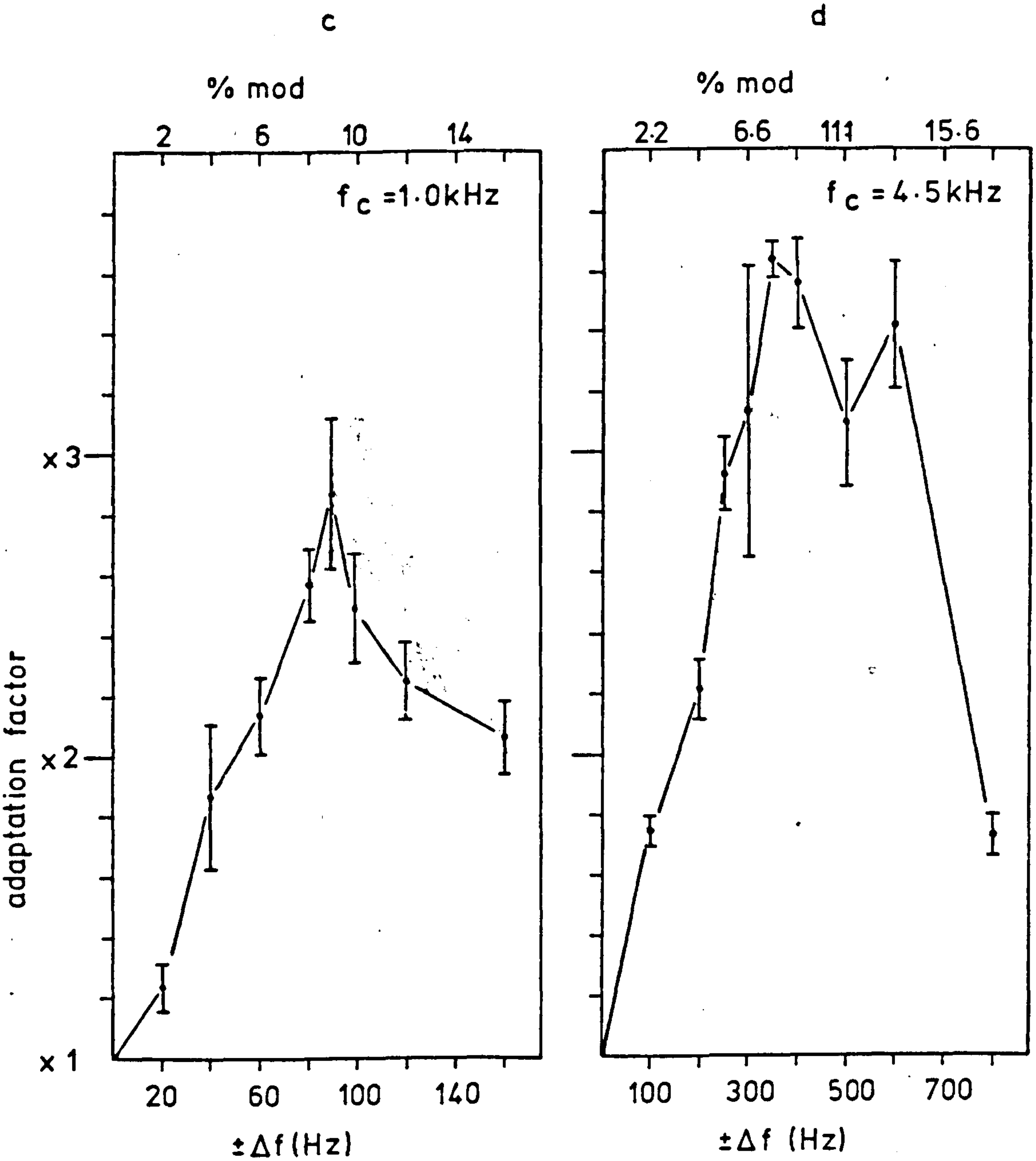
(b) f_c = 0.5 kHz, RBG

(c) f_c = 1.0 kHz, RBG

(d) f_c = 4.5 kHz, RBG

(e) f_c = 1.0 kHz, VJG


a
b
% mod
8
24
40
% mod
4
12
20
f_c = 0.25 kHz
f_c = 0.5 kHz
adaptation factor
x 3
x 2
x 1
20
60
100
±Δf (Hz)
20
60
100
±Δf (Hz)



c
d
% mod
2
6
10
14
f c =1·0kHz
% mod
2·2
6·6
11·1
15·6
f c =4·5kHz
adaptation factor
x 1
x 2
x 3
20
60
100
140
±Δf (Hz)
100
300
500
700
±Δf (Hz)

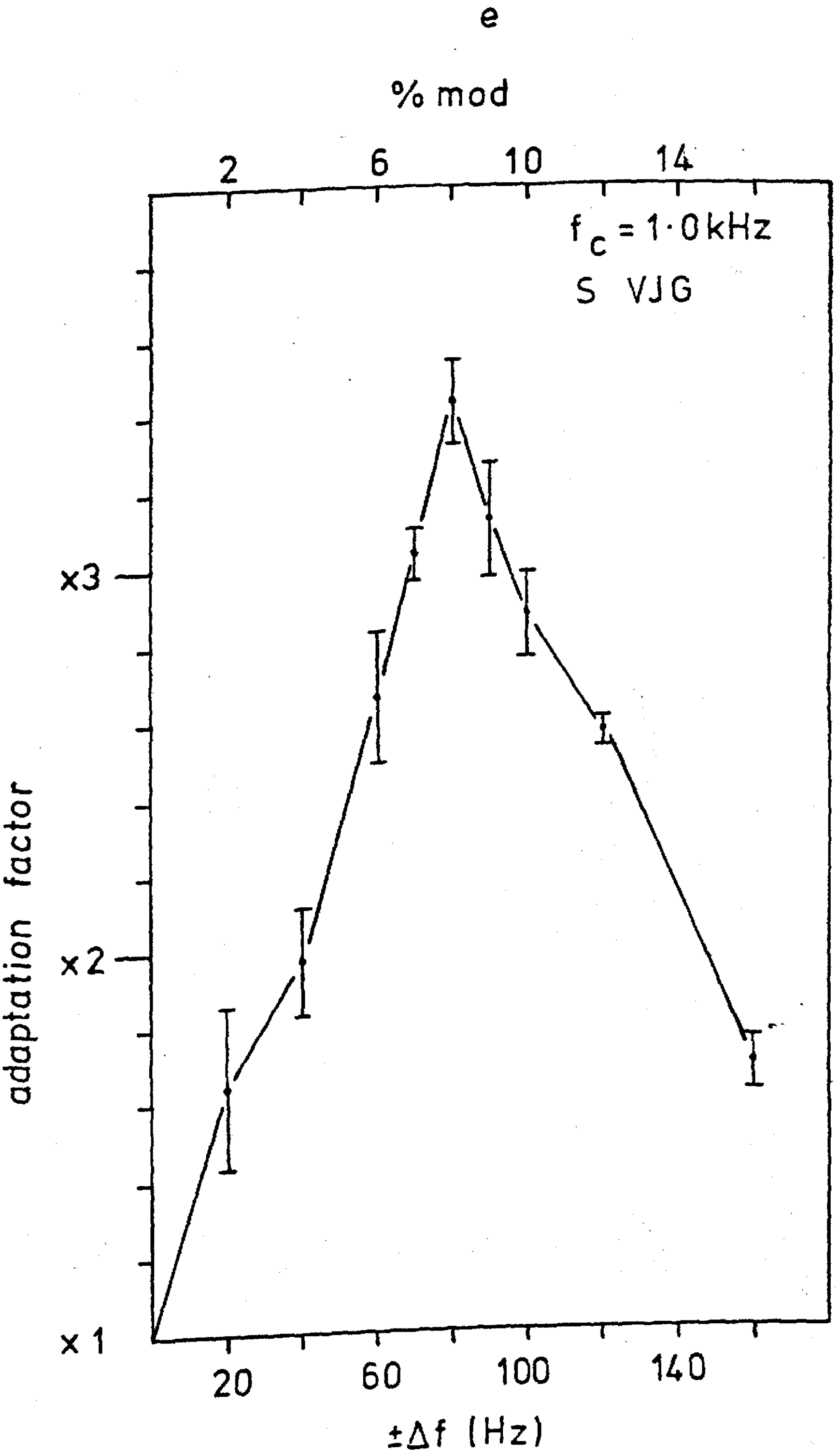
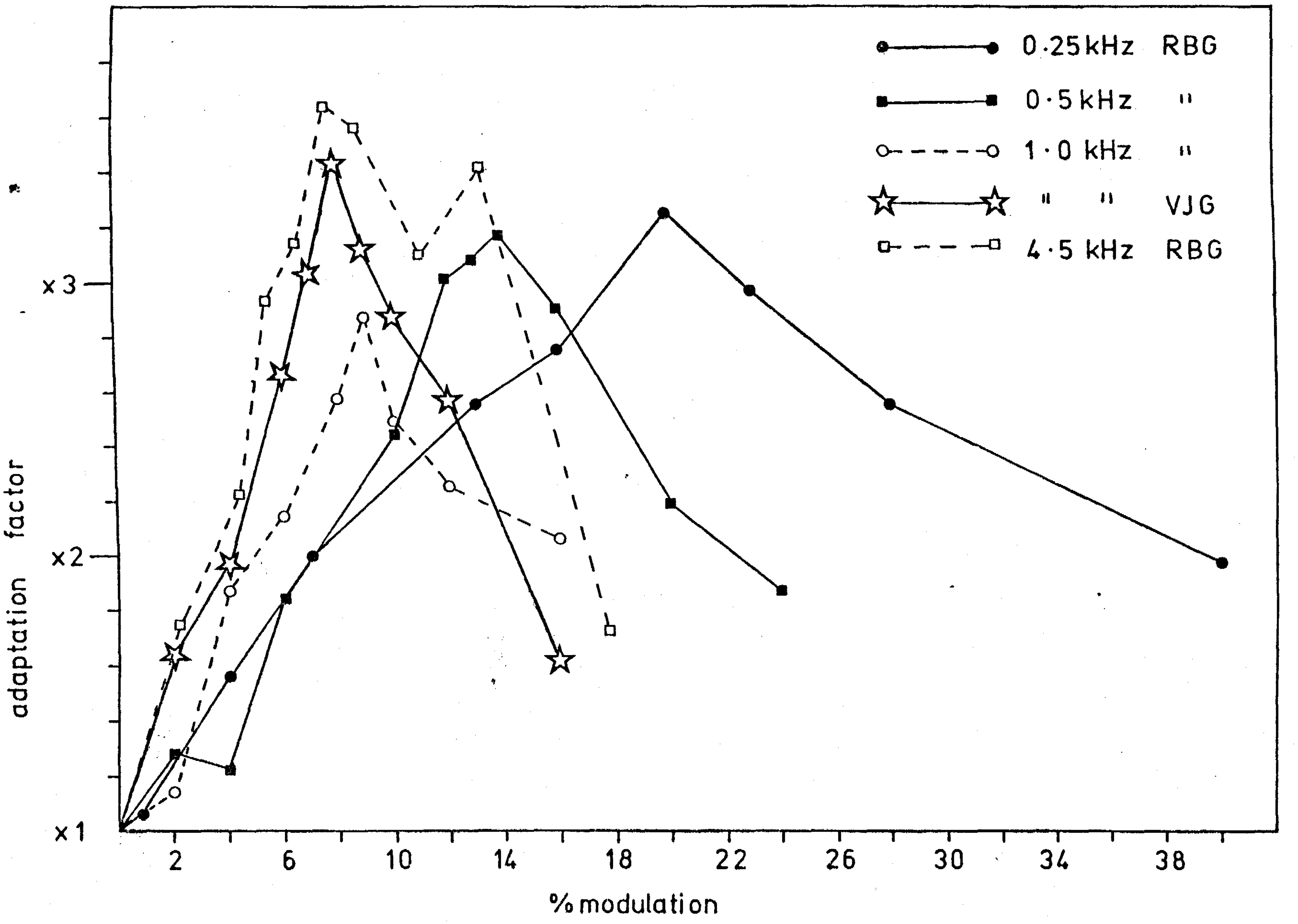

e
% mod
2
6
10
14
$f_c = 1\cdot0$ kHz
S VJG
adaptation factor
x3
x2
x1
20
60
100
140
±Δf (Hz)

Fig. 3.2. Plots of adaptation factor as a function of percentage modulation ($\pm\Delta F/F_c\%$) of adapting stimulus where F_c is the parameter. See figure for key.



0·25 kHz RBG
0·5 kHz "
1·0 kHz "
" " VJG
4·5 kHz RBG
x 3
x 2
x 1
adaptation factor
2
6
10
14
18
22
26
30
34
38
% modulation

all functions are of roughly the same shape showing a linear increase in adaptation with increasing ±ΔF up to some limit (the peak modulation value, PMV) after which adaptation decreases, at a lower rate, with further increases in ±ΔF. Table 3.1 shows values of ±ΔF (hz) used. Fig. 3.2 shows these data plotted against percentage modulation with centre-frequency (f_c) as the parameter.

To compare the slopes of the functions, normalization of both adaptation factor (ADAPT) and ±ΔF was carried out to remove the dependence of the actual values of these variables upon centre frequency. Normalized values were expressed as a percentage where:

$$\pm\Delta F_{norm} = \pm\Delta F / \pm\Delta F_{max} \times 100$$

$$ADAPT_{norm} = (ADAPT-1)/(ADAPT_{max}-1) \times 100$$

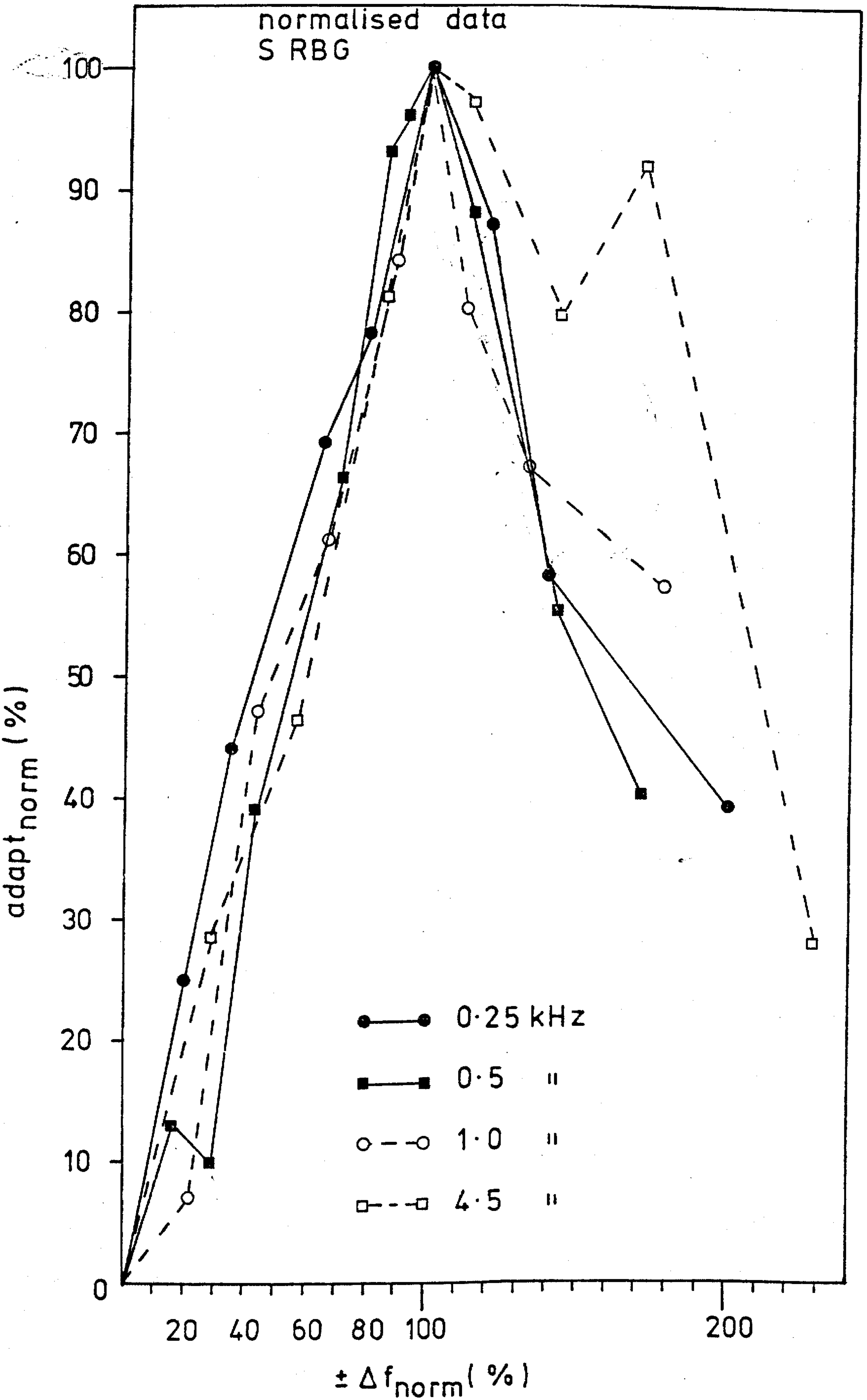
where $\pm\Delta F_{max}$ is the peak modulation value (PMV) and $ADAPT_{max}$ the adaptation factor at this value. These are shown in Table 3.2. Thus each value of ±ΔF is expressed as a percentage of the PMV and adaptation as a percentage of the maximum adaptation at that frequency. Data are plotted in Fig. 3.3 with f_c as the parameter. The fit for the rising part of the function is close and approximately linear. Slopes after the peak are also close except for 4.5 kHz.

3.2 The dependence of adaptation upon ±ΔF: A simple model

3.2.1 Introduction

One way of explaining the data is to invoke a filter in the frequency domain such that increasing frequency deviations within the filter bandwidth would produce an increasing output and greater adaptation. When the frequency deviation entirely fills the bandwidth adaptation would be greatest (the peak of the functions described in section 3.1.2). The PMV (Table 3.2)

Fig. 3.3 Plots of normalised adaptation versus normalised frequency deviation with F_c as the parameter. RBG only. See figure for key.


normalised data
S RBG
adapt$_{norm}$ (%)
0
10
20
30
40
50
60
70
80
90
100
20
40
60
80
100
200
± Δ f$_{norm}$ (%)
0·25 kHz
0·5 "
1·0 "
4·5 "

would equal the effective filter bandwidth. In its simplest form the model proposed a rectangular filter with a centre frequency equal to that of the sweeps. The area under the modulating waveform within the filter bandwidth was taken as a measure of filter output and therefore adaptation. For frequency excursions beyond the filter bandwidth, i.e. greater than the PMV, the area under the waveform within the filter would begin to decrease; the duration of the sweep within the filter would decrease. The decline in adaptation at high frequency deviations would be due to this decrease in duration or increase in rate of change of frequency. This is illustrated in Fig. 3.4a and b.

The area under a quarter cycle of the waveform was the quantity determined. The analysis at 0.25 kHz is described below. The area was determined with ±ΔF as the amplitude. The bandwidth of the rectangular filter was ±50Hz, the PMV. For frequency deviations less than or equal to the filter bandwidth the area was equal to the waveform amplitude and therefor ±ΔF. This gave a linear relationship between adaptation (expressed as the area as a percentage) and ±ΔF (see Fig. 3.5). For frequency excursions in excess of the bandwidth the area was:

$$A = a - \sqrt{a^2 - b^2}$$

where a is the amplitude (±ΔF)

b is the bandwidth.

The derivation for this formula is given in Appendix A.

The curve derived from this model is shown in Fig. 3.5. The empirical curve at 0.25 kHz is drawn for comparison. Adaptation was converted to a normalised scale by the formula given in Section 3.1.3.

Though a good fit is obtained for values of ±ΔF below the PMV the fit is poor for larger values of ±ΔF. This model was rejected.

Fig. 3.4.a Illustration of terms used in analysis of area under modulating waveform (see text).

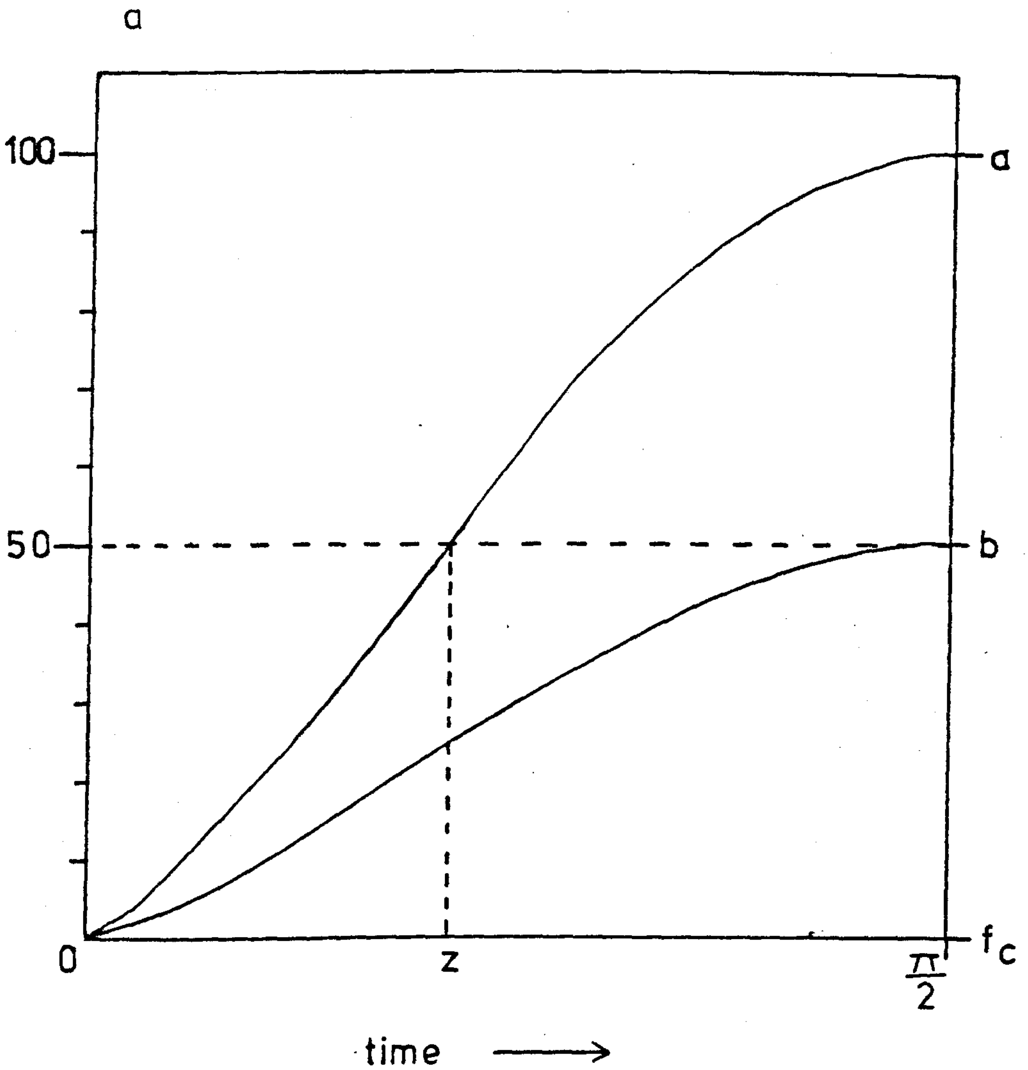

a
100
50
0
a
b
f
c
z
π/2
time →

Figure 3.4b and c

These figures serve to illustrate further the models described in Sections 3.2 and 3.4 (pp.53-59).

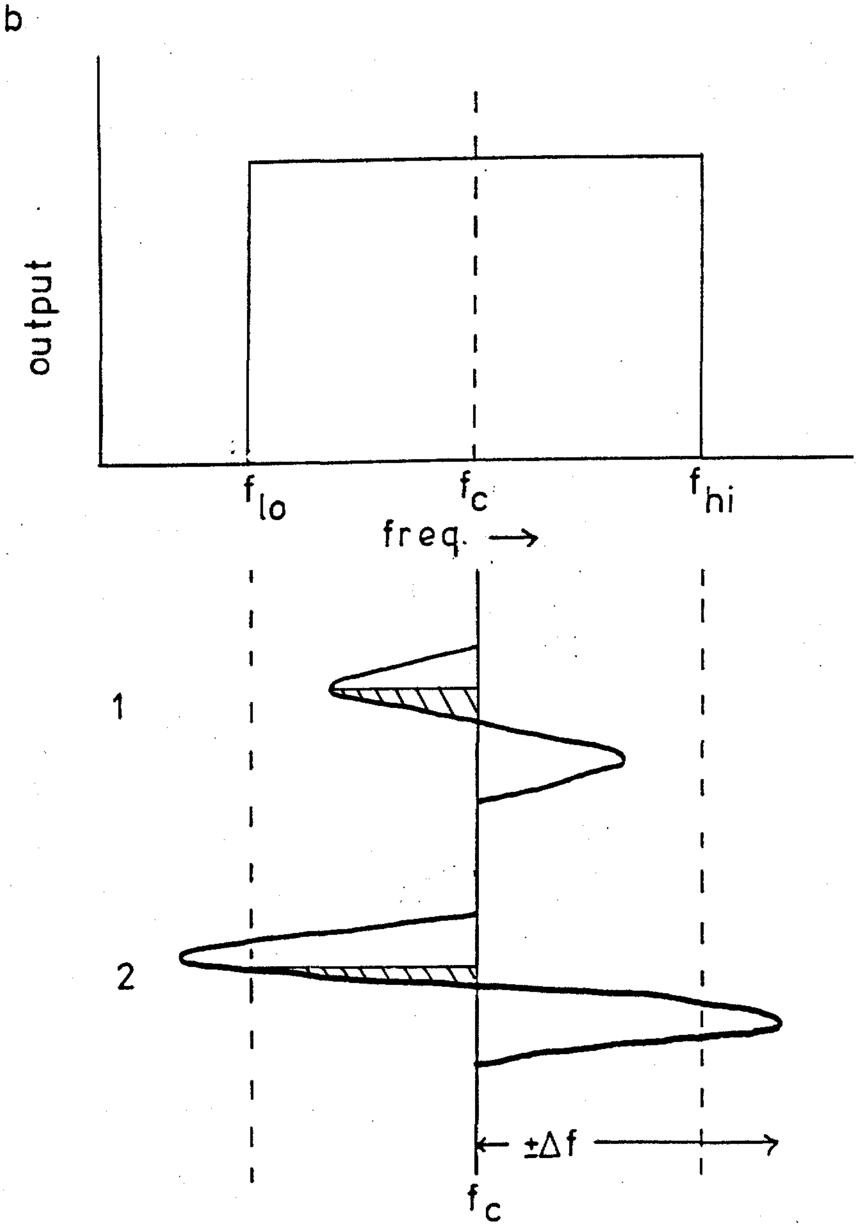
(b) Illustration of (rectangular) filter model. F_c is the centre-frequency of the filter and the frequency transitions. The filter is assumed to be symmetrical. F_{lo} and F_{hi} are the lower and higher cut-off frequencies of the rectangular filter (for the Gaussian filter model on p.58 these would refer to the frequencies corresponding to σ of the Gaussian function). Values of F_{lo} and F_{hi} are equal to b, the filter bandwidth, (see p.54 and Fig. 3.4a), given by the PMV. The lower diagram of Fig. 3.4b shows two examples of sinusoidal-FM modulating waveforms. The dotted vertical lines represent the filter bandwidths.

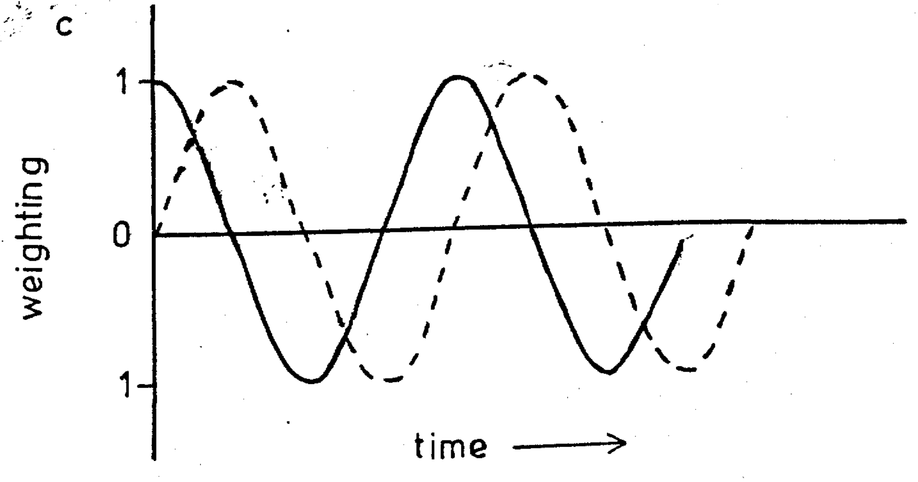
(1) The value of ±ΔF is less than the filter bandwidth. In this case the area under a quarter cycle of the waveform is calculated (shaded area); this area is assumed to give a measure of filter output and adaptation. In these terms adaptation would be greatest when the frequency deviation (±ΔF) was equal to the filter bandwidth.

(2) The value of ±ΔF is greater than the filter bandwidth. In this case the area under the sweep <u>within</u> the filter was calculated (shaded area). As ±ΔF increases beyond the filter bandwidth the duration of the (constant ±ΔF) sweep <u>within</u> the filter decreases. This was a central assumption of the model concerning the decline in adaptation with high values of ±ΔF found in the functions of adaptation factor versus adapting ±ΔF and was tested empirically (Section 3.3, p.56).

(c) Illustration of the cosinusoidal weighting function. The solid line is the cosine function, the dashed line represents the sinusoidal-FM modulating waveform. A weighting of 1 (a peak or trough of cosine function) is given to the zero crossing point (the point at which the frequency of the stimulus crosses F_c) of the sinusoidal waveform, and 0 to the peak of the sinusoidal waveform. Thus a higher weighting is given to the highest rates-of-change of frequency (df/dt) of the modulating waveform than to the peaks where df/dt approaches zero.

Thus, in the situation where ±ΔF exceeds the hypothesised filter bandwidth the loss of the peaks and troughs (the high and low frequency extremes of the modulating waveform) has relatively less effect on adaptation than the loss of higher df/dt portions of the sinusoidal frequency transitions. It must be pointed out that the use of a cosinusoidal function was rather arbitrary and was intended as a first approximation to the FM processing systems rather broad tuning to df/dt.


b
output
f_{lo}
f_c
f_{hi}
freq. →
1
2
±Δf
f_c


c
weighting
1
0
1
time →

3.2.2 A rectangular filter with weighting function

A cosinusoidal weighting function was applied to the analysis giving:

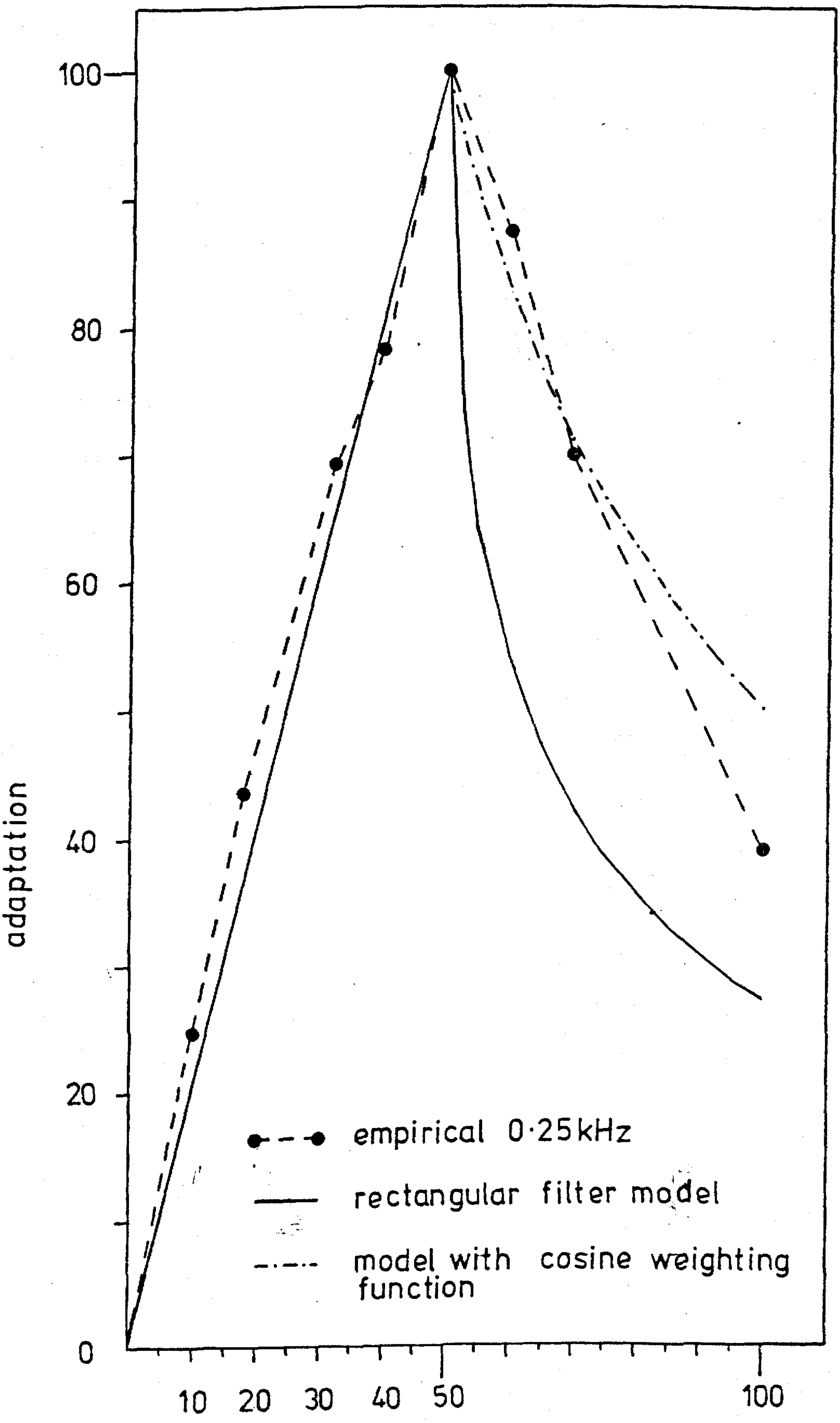
$$A = \int_0^z a \sin x \cos x \, dx$$

The weighting function was introduced to give less weight to the low rates of change of frequency at the peaks and troughs of the sinusoidal modulating-waveform. Though it is true that the FM processing system is broadly tuned to rate of change of frequency there is some empirical justification, presented later, for introducing the weighting function. Less weight is given to the loss of the sinusoid peak for frequency-deviations that just exceed the filter bandwidth than to the loss of higher rates of change portions of the waveform at larger deviations in excess of the bandwidth. (see Fig 3.4 c)

For deviations below the PMV the curve is the same as before. A computer program was written to calculate values of area for deviations between ±55 Hz and ±100 Hz. Areas were converted to a percentage scale and the curve is shown in Fig. 3.5. The fit for the downward portion of the curve is improved.

Before proceeding with an analysis at all frequencies (though Fig. 3.3 would suggest the fit would be good for all frequencies except 4.5 kHz) the major assumption of the model was tested. The assumption is that portions of the sweep outside the filter are lost and the decline in adaptation was due to the increasingly shorter time spent by sweeps within the filter as ±ΔF increased. The introduction of the cosinusoidal weighting function did not fundamentally alter this assumption, i.e. the critical parameter was still the area under the portion of the waveform within the filter.

Fig. 3.5. *Plots of adaptation (normalised) as a function of adapting* ±ΔF at 0.25 kHz. The three curves are the empirical curve for RBG (Fig. 3.1a), predicted curve for the rectangular filter model and the predicted curve for rectangular filter model with a cosinusoidal weighting function.



100
80
60
40
20
0
adaptation
10
20
30
40
50
100
±Δf (Hz)
empirical 0·25kHz
rectangular filter model
model with cosine weighting function

3.3 The dependence of adaptation upon ±ΔF: Linear frequency sweeps

Linear frequency sweeps were used to test the assumption of the model discussed above. With sinusoidal-FM, increases in ±ΔF with a constant repetition rate results in an increase in the mean rate-of-change of frequency and a decrease in the duration of a limited portion of the sweep (e.g. that within the hypothesised rectangular filter). With linear frequency sweeps the rate-of-change of frequency can be held constant over a range of values of ±ΔF by increasing the duration within limits defined by the repetition rate. For an 8Hz rate the maximum duration was set at 120 ms, 5 ms below the cycle time. Linear sweeps provide a direct test of the model because the rate-of-change of frequency and duration of the sweep within the filter can be held constant for sweeps in excess of the hypothesised bandwidth.

3.3.2 Procedure

The experiments were exactly the same as those for sinusoidal-FM as described in Section 3.1.2 except for the substitution of linear sweeps as adapting-stimuli. Unadapted thresholds were the same as before. Both upward- and downward-going frequency sweeps were used. The experiments were carried out at 0.25 and 1.0 kHz for RBG and 1.0 kHz for VJG.

In each experimental condition the adapting sweep duration was held constant for all values of adapting frequency-deviation (±ΔF) except those above the PMV. In this way the rate-of-change of frequency (df/dt) increases with increasing ±ΔF mimicing the similar changes occurring in sinusoidal-FM with increasing ±ΔF and a constant modulation-frequency. For values in excess of the PMV, df/dt was held constant at the PMV value by increasing the sweep duration as ±ΔF increased. The maximum duration was 120 ms. The experiment fulfills two functions:

1. By holding df/dt constant above the PMV the parameters of the sweeps within the filter remain constant and equal to those of the PMV,

i.e. optimal, condition. This allows the assumption of the model concerning the basis of the decline in adaptation at large values of ±ΔF to be tested.

2. By holding the sweep duration constant, at the PMV value, for sweeps with values of ±ΔF below the PMV, the relationship between ±ΔF and adaptation factor can be examined for linear sweeps and compared to those for sinusoidal-FM. At 0.25 kHz the value of df/dt for sweeps at and in excess of the PMV was 1333 Hz/s. At 1.0 kHz the value was 2000 Hz/s for RBG and VJG. An additional curve at 1.0 kHz with a value of df/dt of 1600 Hz/s was determined for RBG. No values in excess of the PMV could be used in this condition as the duration at the PMV was very near the 120 ms limit.

The values of sweep duration at and above the PMV were as follows:

(a) 75 ms in the 0.25 kHz experiment;

(b) 90 ms for RBG at 1.0 kHz, 2000 Hz/s;

(c) 80 ms in the corresponding experiment with VJG;

(d) 112.5 ms in the 1.0 kHz, 1600 Hz/s experiment.

3.3.3 Results and discussion

Curves of adaptation factor versus ±ΔF (Hz) are shown in Fig. 3.6a, b and c. Vertical bar are standard deviations. The curves are roughly the same as those for sinusoidal-FM. At 1600 Hz/s at 1.0 kHz [RBG] the maximum deviation was only ±90 Hz, i.e. the sinusoidal-FM PMV and assumed filter bandwidth at 1.0 kHz, because of the limit to sweep duration imposed by the need for a constant repetition rate. Failure to adhere to this limit by altering repetition rate would have introduced additional variations in adaptation related to the tuning of adaptation to modulation frequency described by Kay and Matthews (1972). For upward-sweeps at 1.0 kHz and 1000 Hz/s the PMV value for RBG is shifted downwards by 10 Hz though it is worth noting that the peak is not as distinct as for sinusoidal FM and, indeed, downward-sweeps. For downward-sweeps at 1600 Hz/s the adaptation is roughly equal from ±40 to ±90 Hz (Fig. 3.6b). The upward-sweep curve at

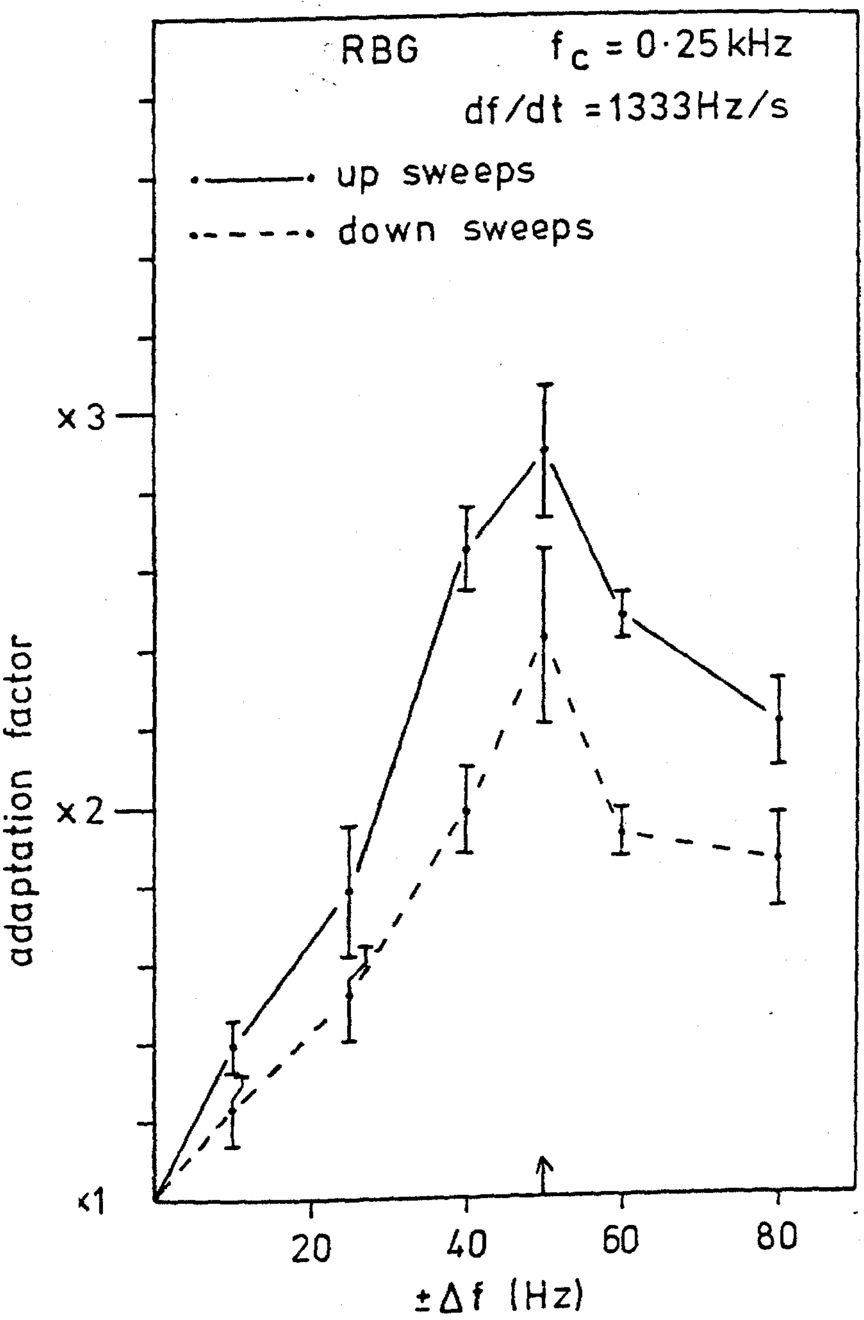
Fig. 3.6a-c. Plots of adaptation factor as a function of adapting ±ΔF for linear sweep adapting stimuli (upward- and downward-going).

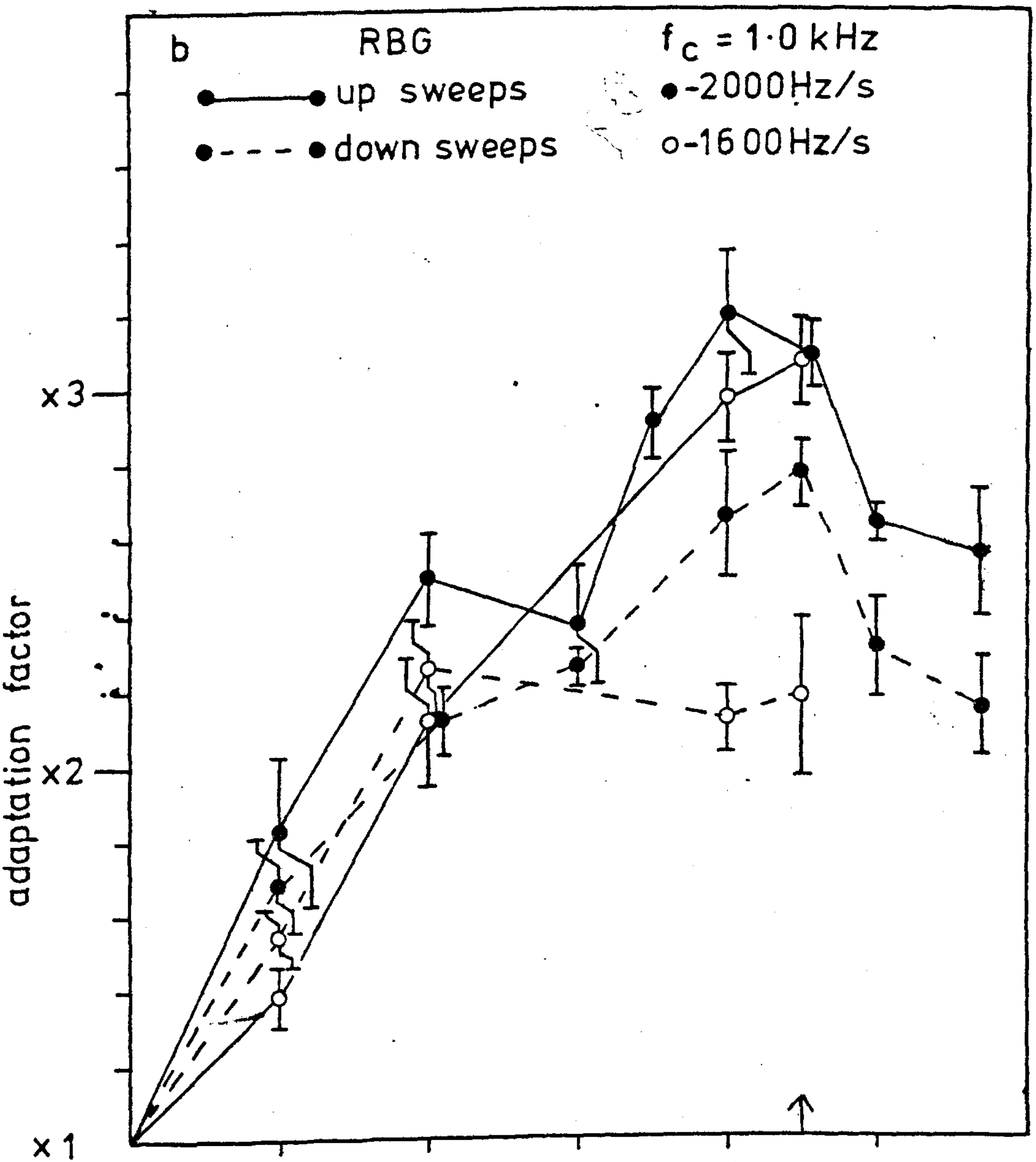
(a) 0.25 kHz, RBG

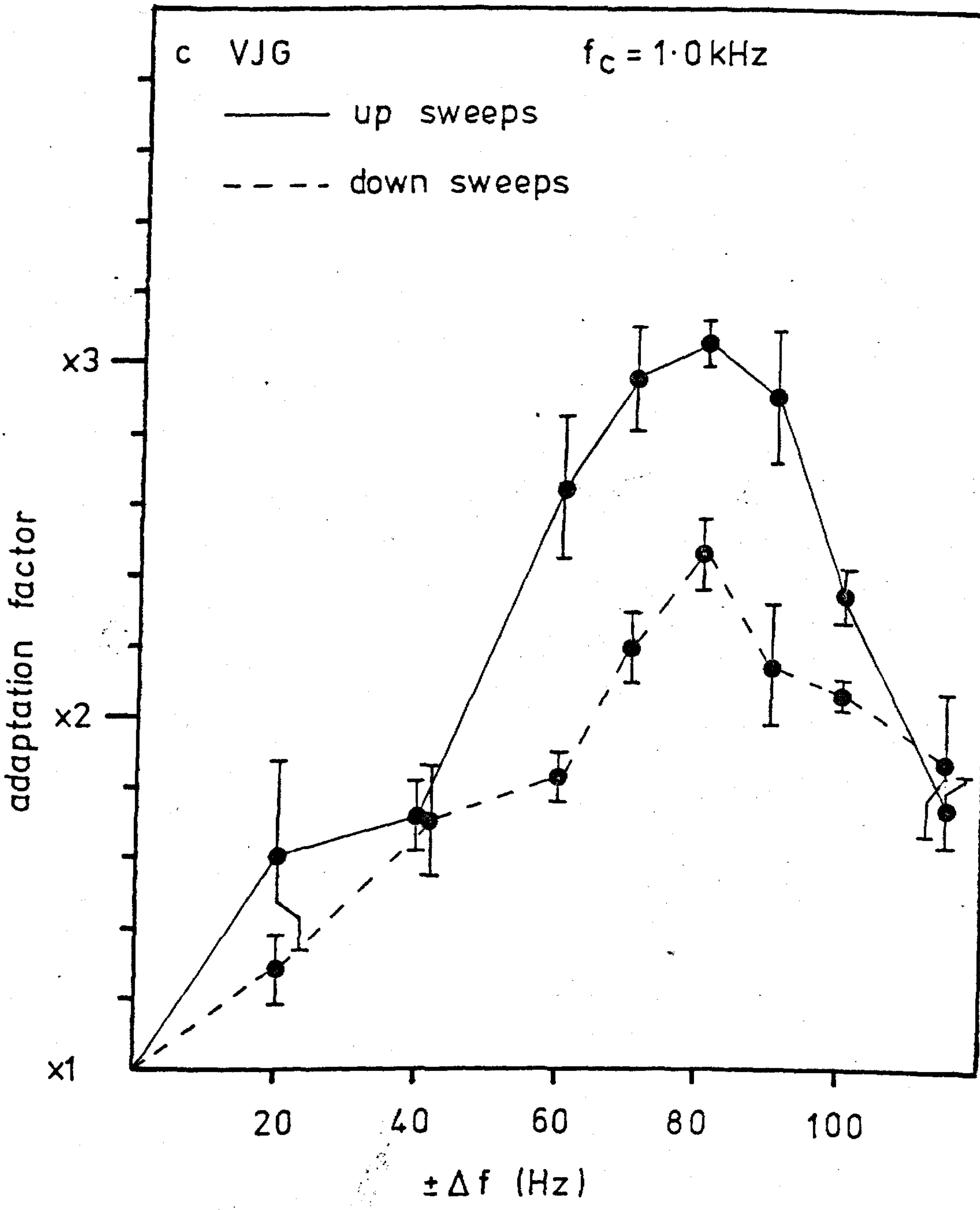
(b) 1.0 kHz, RBG

(c) 1.0 kHz, VJG

The values of df/dt refer to the value of this variable at the PMV maintained for values of ±ΔF greater than the PMV.


RBG
$f_c = 0\cdot25$ kHz
df/dt =1333Hz/s
up sweeps
down sweeps
adaptation factor
×3
×2
×1
20
40
60
80
±Δf (Hz)


b
RBG
f$_c$ = 1·0 kHz
up sweeps
down sweeps
●-2000Hz/s
o-1600Hz/s
x 3
x 2
x 1
adaptation factor
20
40
60
80
100
± Δf (Hz)


c VJG
$f_c = 1{\cdot}0$ kHz
up sweeps
down sweeps
adaptation factor
x3
x2
x1
20
40
60
80
100
±Δf (Hz)

1600 Hz/s shows a similar function to sinusoidal-FM. Other findings are the dependence of adaptation upon df/dt (Fig. 3.7b) and the general finding that downsweep-adaptation is less than upsweep-adaptation. Both these factors are discussed in later chapters. The values of PMV and peak adaptation are summarised in Table 3.4.

Of primary importance is the finding that the decline in adaptation still occurs for large frequency-deviations when the hypothesised filter would be expected to contain a sweep of constant duration. It can be concluded that the model described earlier does not provide an adequate explanation for the decline in adaptation at large frequency deviations. Further, the decline as measured must be due to the presence of the portion of the sweep outside the filter because sweep parameters within the filter remain constant. One possibility is the presence of lateral inhibitory side-bands (see App. D)

3.4 Elaboration of the filter model

Though the model discussed above cannot explain the decline in adaptation found at larger frequency-deviations, it was felt that the analysis in terms of the area under the modulating-waveform within the filter was a fruitful approach to the understanding of the relationship between adaptation and adapting frequency deviation below the PMV.

The analysis was continued with a more realistic Gaussian filter with a bandwidth (σ) equal to the PMV for sinusoidal-FM (Table 3.2). The formula was:

$$A = \int_{\frac{\pi}{2}}^{0} a \sin x \, e^{-(a \sin x)^2/2\sigma^2} \, dx$$

where a is the frequency deviation ±ΔF (Hz)

σ is the Gaussian bandwidth.

The filter was assumed to be symmetrical around the centre frequency. A computer program was written to produce the values of A at 0.25, 0.5, 1.0

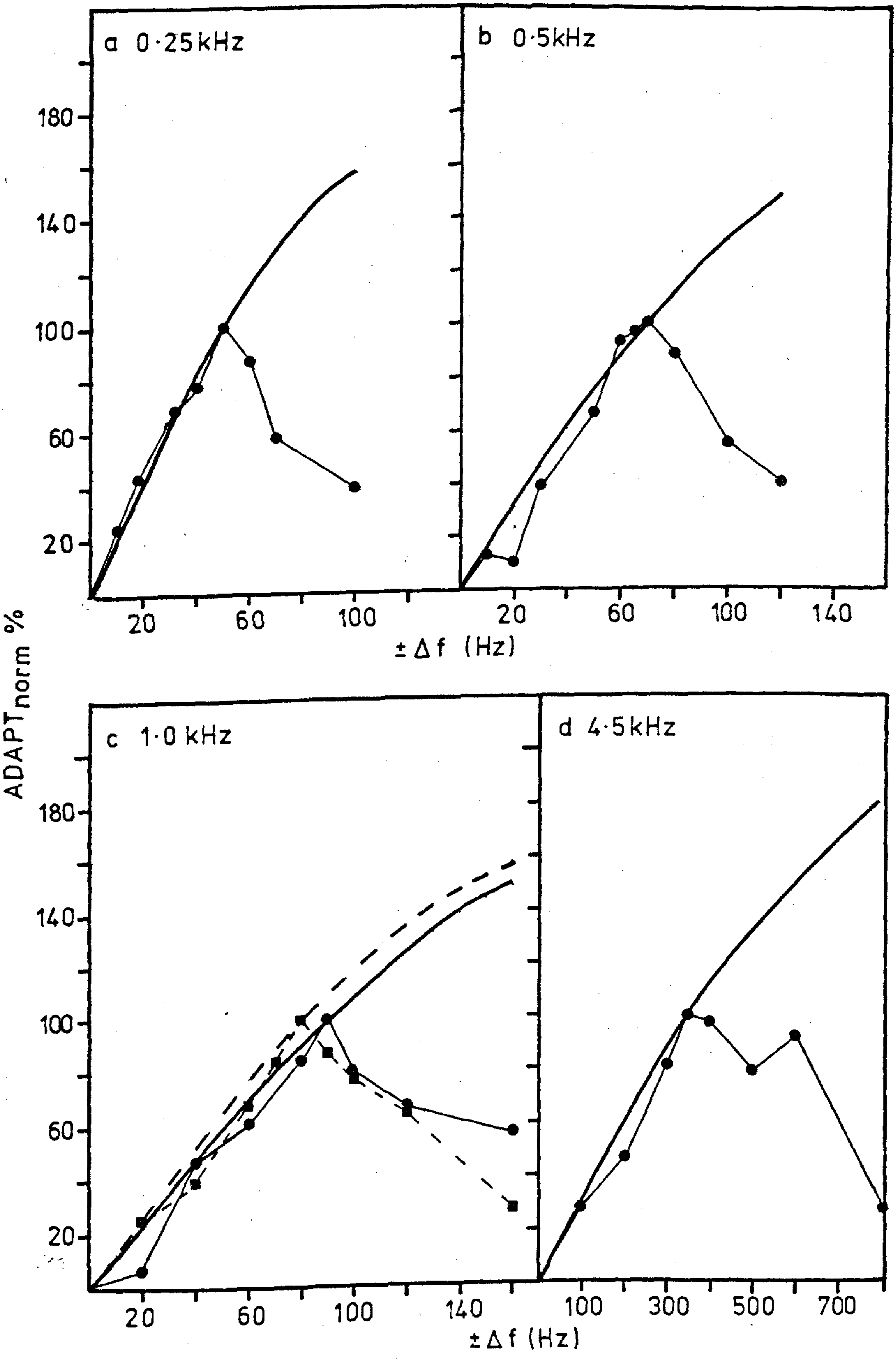
and 4.5 kHz for RBG and 1.0 kHz for VJG. Values of the bandwidth are given in Table 3.5. Figure 3.7a-d shows plots of the Gaussian predicted curves against normalised empirical curves for all centre-frequencies and both subjects. A good fit was obtained up to the PMV after which lateral effects predominate.

3.5 Summary and discussion

Evidence is provided for filters in the frequency domain flanked by lateral inhibitory side-bands. Curves of adaptation versus adapting frequency-deviation for sinusoidal-FM show a distinct pattern consisting of a linear increase in adaptation with increasing frequency deviation up to a peak (the PMV) after which further increases in frequency-deviation result in a progressive decrease in adaptation.

A filter having a bandwidth equal to the PMV was hypothesised such that increasing frequency deviations within the filter would result in an increased output and greater adaptation. The area under the modulating waveform within the filter bandwidth was found to be an adequate measure of adaptation. The decrease in adaptation was also found for linear sweeps where the sweep parameters within the hypothesised filter bandwidth remained constant. This implies the extremes of the sweeps outside the filter activate lateral inhibitory mechanisms producing a decrease in filter output, and therefore adaptation. Though the sweep parameters within the filter can be held constant for linear sweeps, this is not so for sinusoidal FM where a progressive decrease in sweep duration occurs with increases in frequency-deviation beyond this bandwidth. As will be seen later the FM system is sensitive to variations in duration of constant ±ΔF sweeps. A steady decrease in duration might be expected to act with the lateral inhibitory effects to promote the decline in adaptation. This is not reflected in the slopes found for sinusoidal FM compared with those for linear frequency sweeps (Fig. 3.8).

Fig. 3.7a-d. Plots of adaptation (norm) as a function of adapting ±ΔF of sinusoidal-FM (see Fig. 3.1a-e), showing predicted curves from Gaussian filter model (thicker lines).


a 0·25kHz
b 0·5kHz
c 1·0 kHz
d 4·5kHz
ADAPT$_{norm}$ %
180
140
100
60
20
20
60
100
20
60
100
140
±Δf (Hz)
20
60
100
140
100
300
500
700
±Δf (Hz)

Good fits to the rising part of the functions were obtained with symmetrical Gaussian filters centred on the centre-frequency of the FM stimuli (0.25, 0.5, 1.0 or 4.5 kHz) and with bandwidths (σ) equal to the PMV at these frequencies. Empirical justification for the use of Gaussian filters comes from Patterson (1974; 1976). The relationship between the empirically derived FM filter bandwidth and the critical bandwidth (Scharf, 1970) is shown in Fig. 3.9. The closeness of actual values and the similarity of the functions suggest the FM filter is based on the same mechanism underlying the critical band measures.

In summary, the relationship between adaptation and adapting frequency-deviation reveals the existence and bandwidth of frequency selective filters in the FM processing system analogous to that of Kay and Matthews (1972) at 0.25 kHz.

The following chapter compares these bandwidths with those measured by the Kay and Matthews (1972) method.

Fig. 3.8. Plots of adaptation (normalised) as a function of normalised frequency-deviation after the PMV ($\pm\Delta F_{norm} = 100\%$).

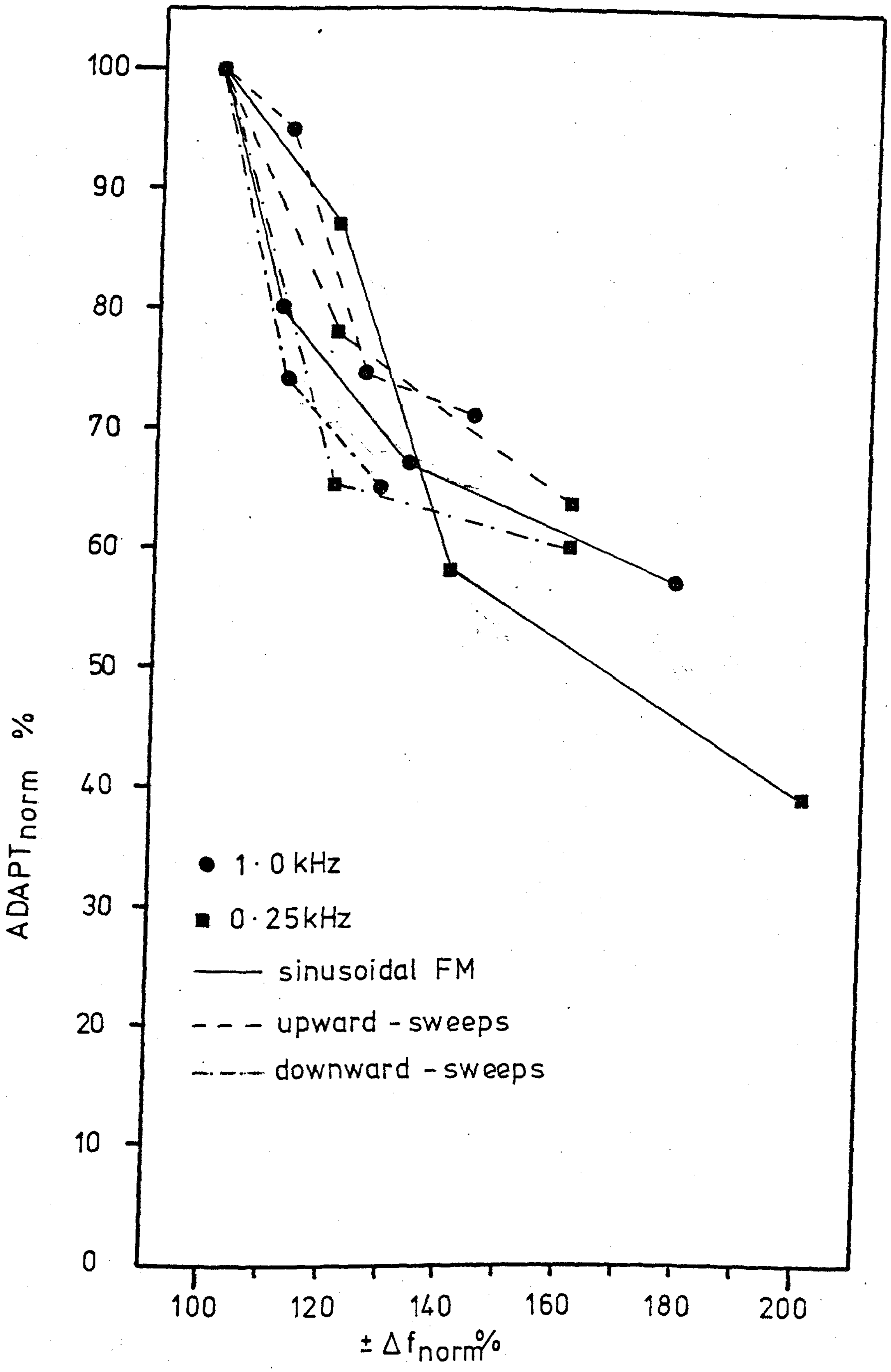

ADAPT$_{norm}$ %
100
90
80
70
60
50
40
30
20
10
0
100
120
140
160
180
200
± Δf$_{norm}$%
● 1·0 kHz
■ 0·25kHz
sinusoidal FM
upward - sweeps
downward - sweeps

Fig. 3.9. • FM filter bandwidths derived from this chapter and critical bandwidths (Scharf, 1970) expressed in Hz as a function of F_c (kHz).

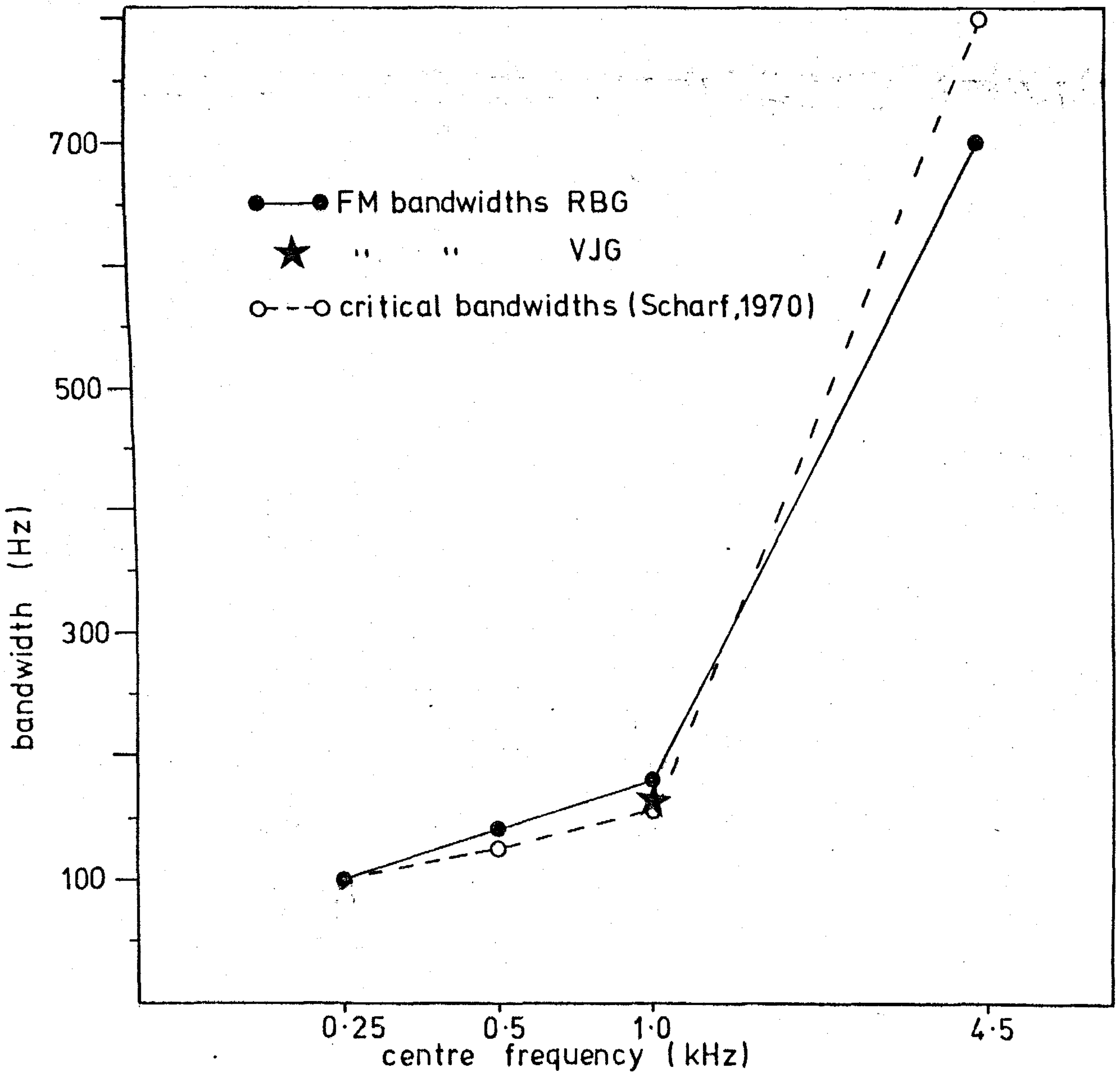

FM bandwidths RBG
" " VJG
critical bandwidths (Scharf,1970)
700
500
300
100
bandwidth (Hz)
0·25
0·5
1·0
4·5
centre frequency (kHz)

TABLE 3.1

RBG 0.25 kHz ±ΔF (Hz)	RBG 0.5 kHz ±ΔF (Hz)	RBG 1.0 kHz ±ΔF (Hz)	RBG 4.5 kHz ±ΔF (Hz)	VJG 1.0 kHz ±ΔF (Hz)
0	0	0	0	0
2.5	10	20	100	20
10	20	40	200	40
17.5	30	60	250	60
32.5	50	80	300	70
40	60	90	350	80
50	65	100	400	90
60	70	120	500	100
70	80	160	600	120
100	100		800	160
	120			

Values of adapting frequency-deviation of sinusoidal-FM (see Section 3.1.2, Fig. 3.1a-e).

TABLE 3.2

F_c (kHz)	PMV [±ΔF (Hz)]	$ADAPT_{max}$
0.25	50	3.25
0.5	70	3.17
1.0	90	2.87
4.5	350	3.64
1.0 (VJG)	80	3.43

Values of frequency-deviation producing maximum adaptation ($ADAPT_{max}$), i.e. the peak modulation value (PMV), at each centre-frequency. The values of PMV are assumed to represent the bandwidths of the hypothesised filters in the carrier frequency domain.

TABLE 3.3

0.25 kHz 1333 Hz/s	1.0 kHz 1600 Hz/s	1.0 kHz 2000 Hz/s
0	0	0
10	20	20
25	40	40
40	80	60
50	90	70
60		80
80		90
		100
		115

Values of adapting frequency-deviation expressed as ±ΔF (Hz) for the linear frequency sweep experiments (Section 3.3.2, Fig. 3.6a-c). Values were the same for upward- and downward-going sweeps and for both subjects.

TABLE 3.4

F_c (kHz) $\frac{df}{dt}$ (Hz/s)	SWEEP DIRECTION	PMV [±ΔF (Hz)]	$ADAPT_{max}$
0.25	UP	50	2.89
1333	DOWN	50	2.42
1.0	UP	80	3.19
2000	DOWN	90	2.76
1.0	UP	80	3.05
2000 (VJG)	DOWN	80	2.45

Values of PMV in Hz and associated values of adaptation for linear sweep adapting-stimuli (see Fig. 3.6a-c).

TABLE 3.5

F_c (kHz)	Bandwidth σ (± Hz)
0.25	50
0.5	70
1.0	90
4.5	350
1.0 (VJG)	80

Gaussian filter bandwidths used for the analysis described in Section 3.4. Values used are equal to the PMV for sinusoidal-FM described in Table 3.2.

CHAPTER 4

4.1 Introduction

In Chapter 3 plots of adaptation factor against adapting frequency-deviation reveal filters in the carrier-frequency domain with lateral inhibitory side-bands. FM-channels are selectivity tuned to carrier-frequency. Kay and Matthews (1972) determined the frequency selectivity of FM-adaptation by holding the centre-frequency of the test-stimulus constant at 0.25 kHz and varying the adapting centre-frequency. The resultant functions showed a decrease in adaptation as the frequency difference between test and adaptor increased. This "tuning-curve" was taken as a measure of the frequency selectivity of the FM-channel at 0.25 kHz. A best-fit Gaussian curve had a half-height bandwidth of 200 Hz, twice the critical bandwidth at 0.25 kHz and the filter bandwidth found in Chapter 3. Half-height refers to the bandwidth and the value of adaptation half-way between maximum and zero (x 1). A better measure may be σ corresponding to the Gaussian bandwidths of Chapter 3 and given by $[0.607\ (\text{adapt}_{\text{max}} - 1)] + 1$.

The explanation of tuning-curves involves the concept of channels, the test-stimulus being processed by a channel "tuned" to 0.25 kHz. An adapting-stimulus at 0.25 kHz is also processed by this channel and adaptation is greatest (although small peak shifts in tuning curves can occur - see Kay and Matthews (1972) and the results of this chapter). Adapting-stimuli with different centre-frequencies to the test-stimulus produce less adaptation because the test channel is less sensitive to these frequencies and/or interactions between channels are weaker as the frequency difference between them increases.

It was decided to measure tuning-curves at a number of frequencies for comparison with measures of selectivity from Chapter 3.

4.2 Tuning-curves from sinusoidal-FM adapting stimuli

4.2.1 Methods

Experiments were carried out with sinusoidal-FM test-and adapting-stimuli as described in Section 3.2.1 and Chapter 2. The carrier-frequency of the adapting-stimulus was varied with respect to the constant test frequency. Tuning-curves were determined at 0.25, 0.5, 1.0 and 4.5 kHz for RBG and 1.0 kHz for VJG. Three values of adapting frequency-deviation were used at 0.25 and 1.0 kHz, i.e. three separate tuning curves were determined. Values of frequency deviation were: ±32.5 Hz, ±50 Hz (PMV) and ±100 Hz at 0.25 kHz, ±40 Hz, ±90 Hz (PMV) and ±160 Hz for RBG at 1.0 kHz and ±40 Hz, ±80 Hz (PMV) and ±160 Hz at 1.0 kHz for VJG. Adapting frequency-deviation at 0.5 kHz was ±70 Hz (PMV) and ±350 Hz (PMV) at 4.5 kHz. Table 4.1 shows the values of adapting centre-frequency used in the experiments. During the determination of the tuning curves, values of adapting frequency were chosen randomly. Three threshold estimates were made at each value and the mean and standard deviation calculated.

4.2.2 Results and Discussion

Figures 4.1a-d show tuning at all frequencies and data fromboth subjects. For clarity, standard deviations were not drawn but are presented in Table 4.1 together with mean values of adaptation factor. The lower graphs in Fig. 4.1a-c show tuning curves in terms of adaptation factor with adapting frequency-deviation as the parameter. The upper graphs are the same data plotted on a normalised adaptation scale where:

$$\text{adapt}_{\text{norm}}\ \% \;=\; (\text{adapt}-1)/(\text{adapt}_{\text{max}}-1) \times 100$$

where $\text{adapt}_{\text{max}}$ is the value of adaptation factor at the peak of the tuning curves (not always the test frequency value of adaptation). Normalisation, by removing the dependence of adaptation factor upon the parameter, allows better comparisons of bandwidth and slope to be made.

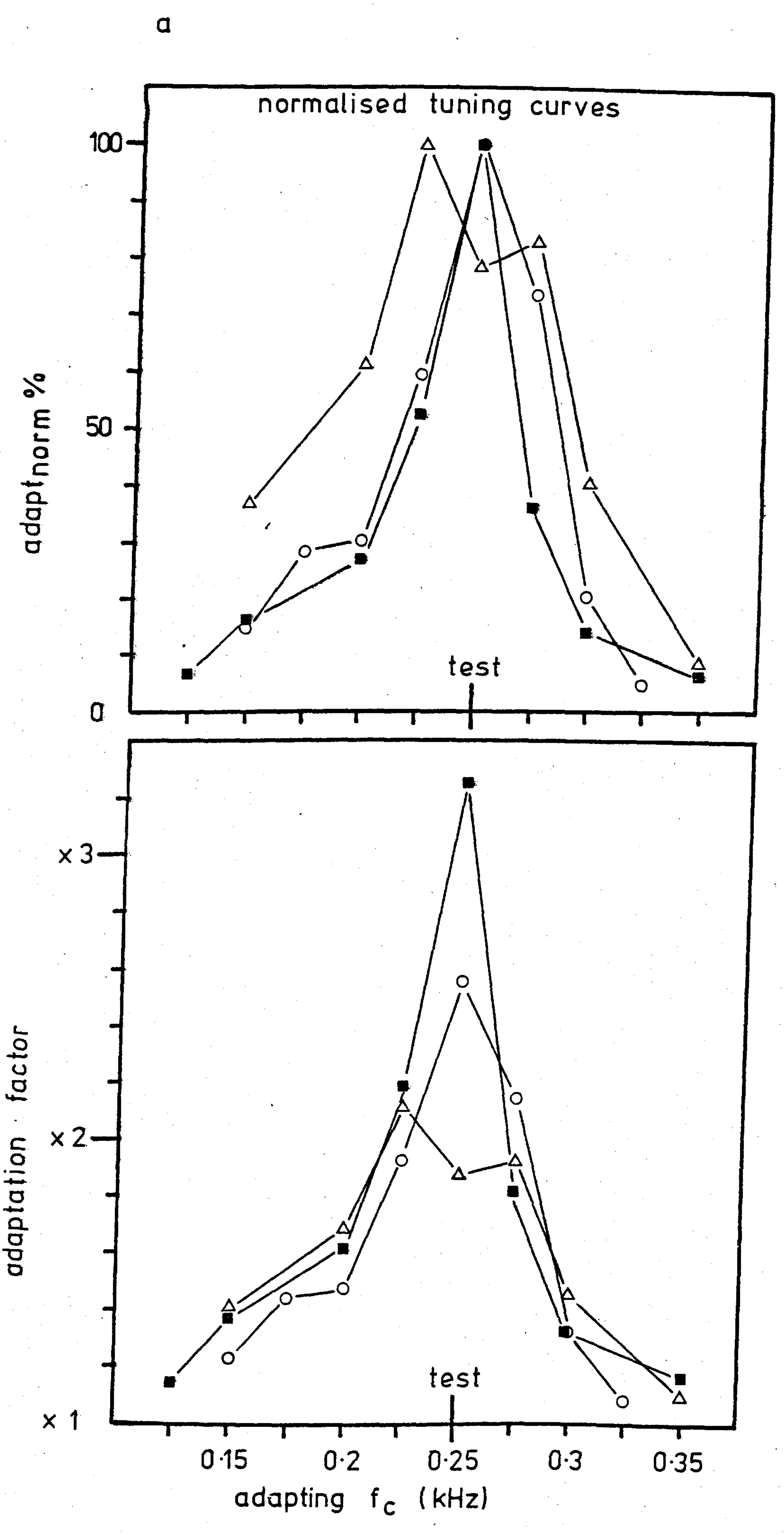
Figure 4.1a-d. Tuning curves in the carrier-frequency domain for sinusoidal-FM adapting-stimuli. In Fig. 4.1a-c, adapting frequency deviation is the parameter. The key to the figures is as follows:

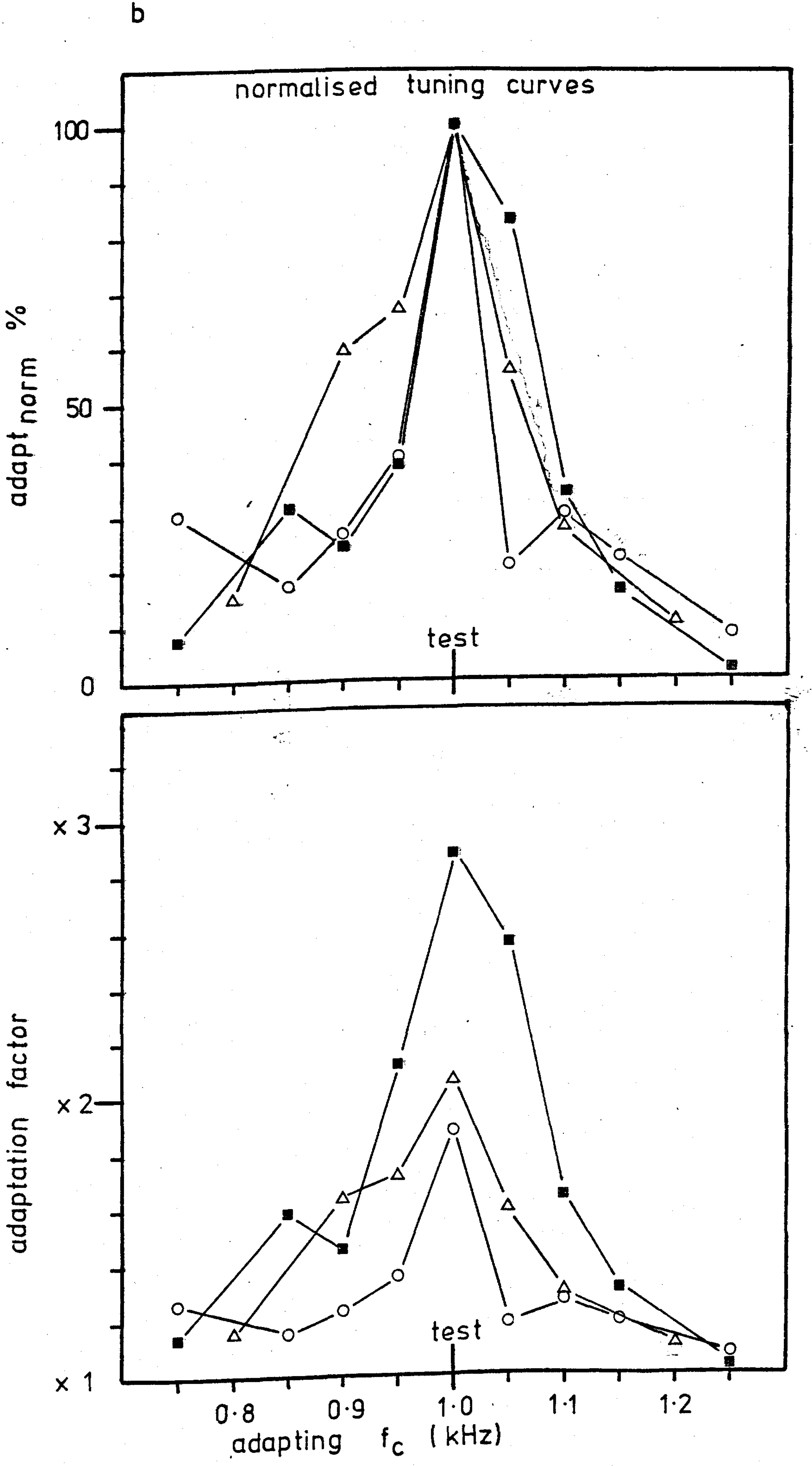
(a) 0.25 kHz; 0——0 ±32.5 Hz, ■——■ ±50 Hz, Δ——Δ ±100 Hz.

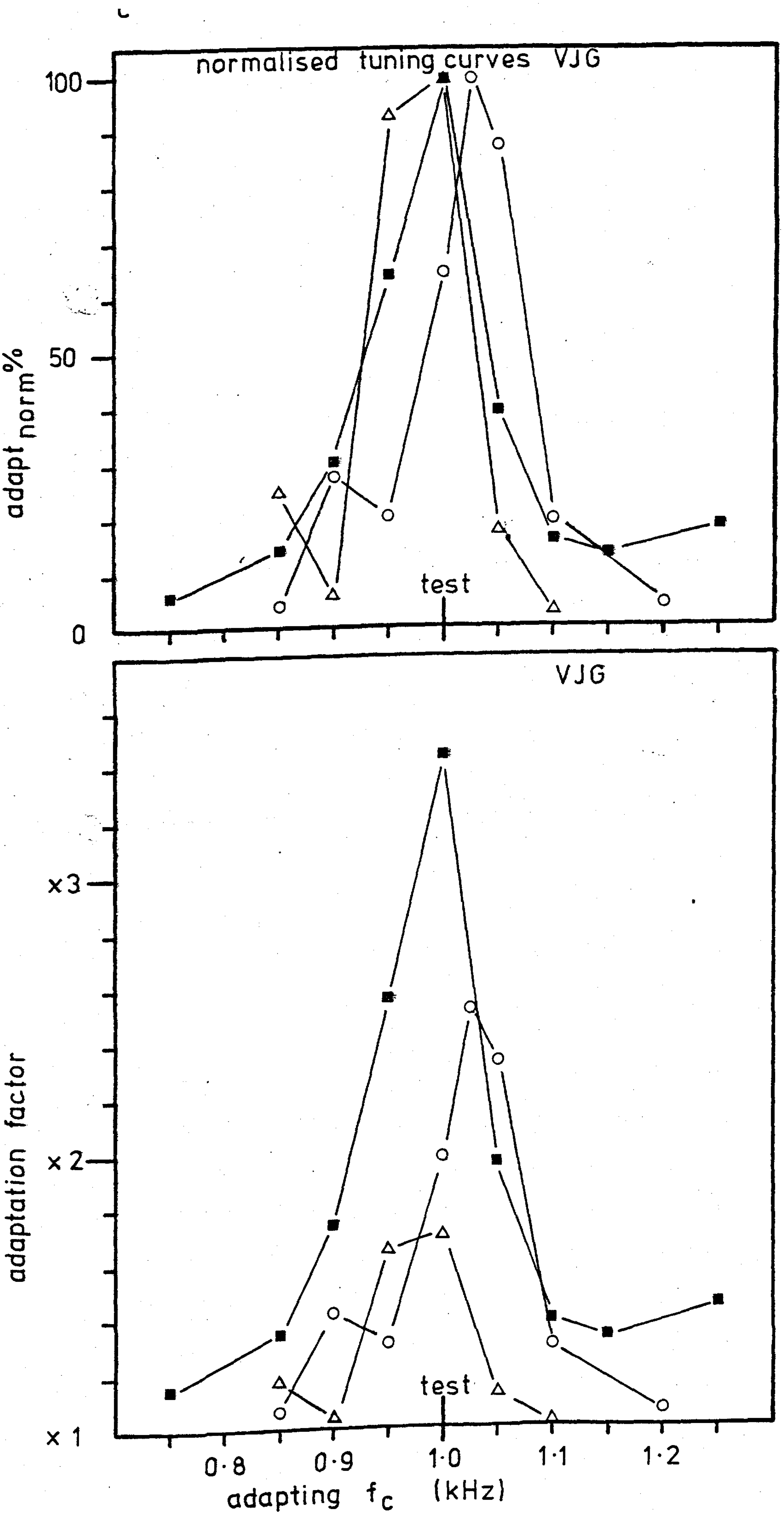
(b) 1.0 kHz (RBG); 0——0 ±40 Hz, ■——■ ±90 Hz, Δ——Δ ±160 Hz.

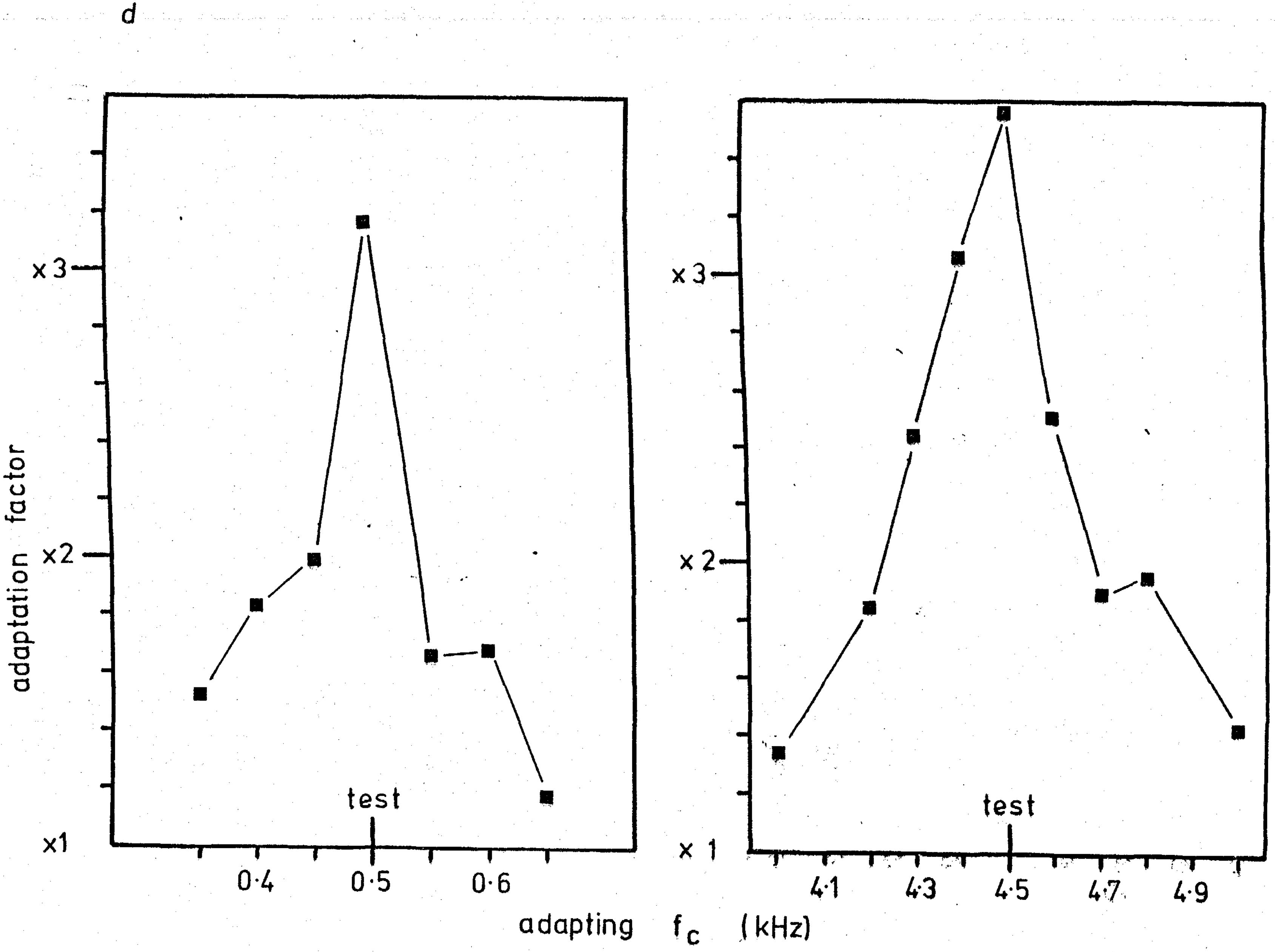
(c) 1.0 kHz (VJG); as above except ■——■ ±80 Hz.

Adapting frequency deviations were ±70 Hz at 0.5 kHz and ±350 Hz at 4.5 kHz.


a
normalised tuning curves
100
50
0
adaptnorm %
test
x 3
x 2
x 1
adaptation factor
test
0·15
0·2
0·25
0·3
0·35
adapting fc (kHz)


b
normalised tuning curves
100
50
0
adapt norm %
test
x 3
x 2
x 1
adaptation factor
test
0·8
0·9
1·0
1·1
1·2
adapting f_c (kHz)


c
normalised tuning curves VJG
100
50
0
adapt$_{norm}$%
test
VJG
×3
×2
×1
adaptation factor
test
0·8
0·9
1·0
1·1
1·2
adapting f_c (kHz)


d
adaptation factor
x1
x2
x3
test
0·4
0·5
0·6
x 1
x 2
x 3
test
4·1
4·3
4·5
4·7
4·9
adapting f_c (kHz)

The data confirm the existence of frequency selectivity in FM-adaptation as a general property of this adaptation. The curves consist of a sharply tuned portion around the test frequency with wider skirts at the more distant frequencies. The only exception is the ±100 Hz curve at 0.25 kHz. It is interesting to note that the data points of Fig. 7 of Kay and Matthews (1972) (see Fig. 1.1) show a curve with similar characteristics to those found here. The Gaussian curve used to fit the data may be inappropriate. Certainly the discrepancy in bandwidths at 0.25 kHz disappears if the actual data are used to plot the curve. The normalised curves show that except for the ±100 Hz curve at 0.25 kHz and the lower frequency half of the ±160 Hz curve at 1.0 kHz for RBG, the adapting frequency-deviation has little systematic influence upon the bandwidth and slope of the curves. Half-height bandwidths, with the exceptions already mentioned, are narrower than the bandwidths of the Gaussian filters derived from Chapter 3 (Table 4.2). If the bandwidth corresponding to the σ value of the Gaussian curves (taken as Gaussian bandwidth) is calculated, the difference is even greater.

Taking the filters of Chapter 3 as a direct measure of a particular channel's frequency selectivity, the differences between values of adaptation at the test frequency for the three values of frequency deviation is easily explained. The difference between the lowest and PMV value may be due to the induced activity within the "excitatory" area of the filter. At the highest value of ±ΔF the inhibitory side-bands are activated resulting in reduced filter output and therefore adaptation. Thus when test and adapting frequencies are equal the differences in the values of adaptation factor between the parameters are represented in the data and model of Chapter 3. The value of adaptation is dependent upon the parameter but bandwidth and slope are not. The trend seems to be towards a reduction in these differences in adaptation factor between the values of ±ΔF as the difference between test and adapting frequency increases.

The shape of the tuning curves must be due to two main factors.

First, the channel filter characteristic as determined in Chapter 3 where filter output and adaptation factor are dependent upon the centre frequency and frequency range of the adapting frequency transitions. If this influence alone (without lateral inhibitory processes being involved) were present then the tuning-curves would be expected to have a Gaussian ($y = e^{-x^2}$) shape. That this is not so is evidence for the presence of the second factor, namely, lateral inhibition. This would be expected to increase as the difference between test and adapting frequencies increased because relatively larger excursions into the side bands would occur. The tuning curves as measured represent the interaction of these two factors.

4.3 Tuning curves with linear sweep FM

4.3.1 Methods

Experiments were carried out as before but with upward-going linear frequency sweep stimuli. The value of frequency deviation was ±20 Hz at 0.25 and 1.0 kHz (RBG and VJG). Values of adapting frequency deviation were as before except for the additional value of 0.375 kHz in the 0.25 kHz experiment. Three threshold estimates were made at each value and the mean and standard deviations calculated. The value of ±20 Hz was chosen because it produced values of adaptation large enough to show tuning effects without large overlaps in standard deviation bars.

4.3.2 Results and Discussion

Figure 4.2a-c shows tuning curves for both subjects. Vertical bars are standard deviations (±1SD). The low-frequency half of the curve is roughly the same as those for sinusoidal-FM; the high-frequency side, however, reveals threshold facilitation. Thus two effects on threshold, adaptation and facilitation, can be measured.

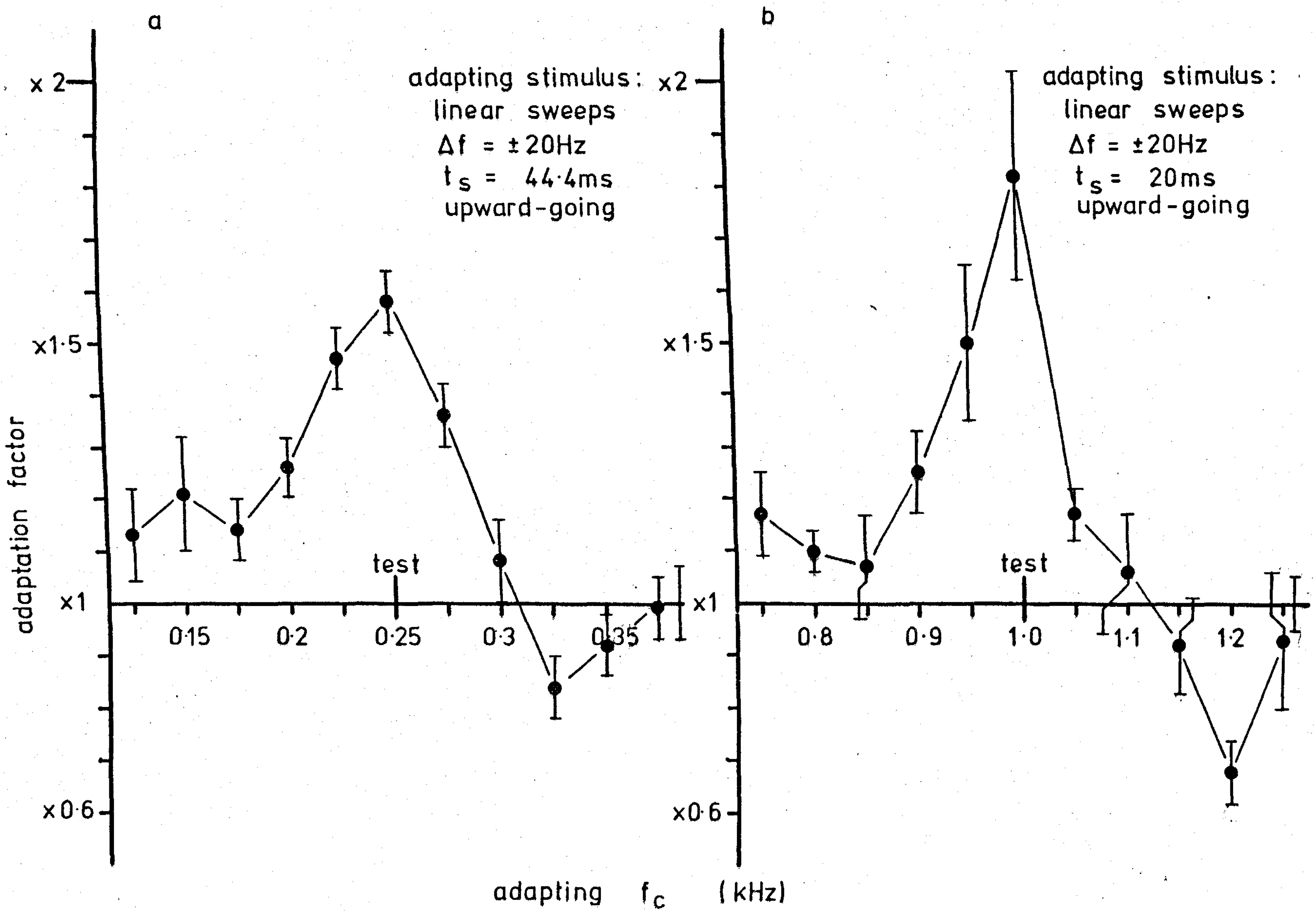
If thresholds are determined by filter output or the activity within a particular tuned channel to an FM test stimulus then adapting

Figure 4.2a-c. Tuning curves in the carrier-frequency domain for linear frequency sweeps at 0.25 and 1.0 kHz. Adapting frequency deviation was ±20 Hz in all conditions.

(a) 0.25 kHz RBG.

(b) 1.0 kHz RBG.

(c) 1.0 kHz VJG.


a
adapting stimulus:
linear sweeps
Δf = ±20Hz
t_s = 44·4ms
upward-going
x 2
x1·5
x1
x0·6
adaptation factor
test
0·15
0·2
0·25
0·3
0·35
b
adapting stimulus:
linear sweeps
Δf = ±20Hz
t_s = 20ms
upward-going
x2
x1·5
x1
x0·6
test
0·8
0·9
1·0
1·1
1·2
adapting f_c (kHz)

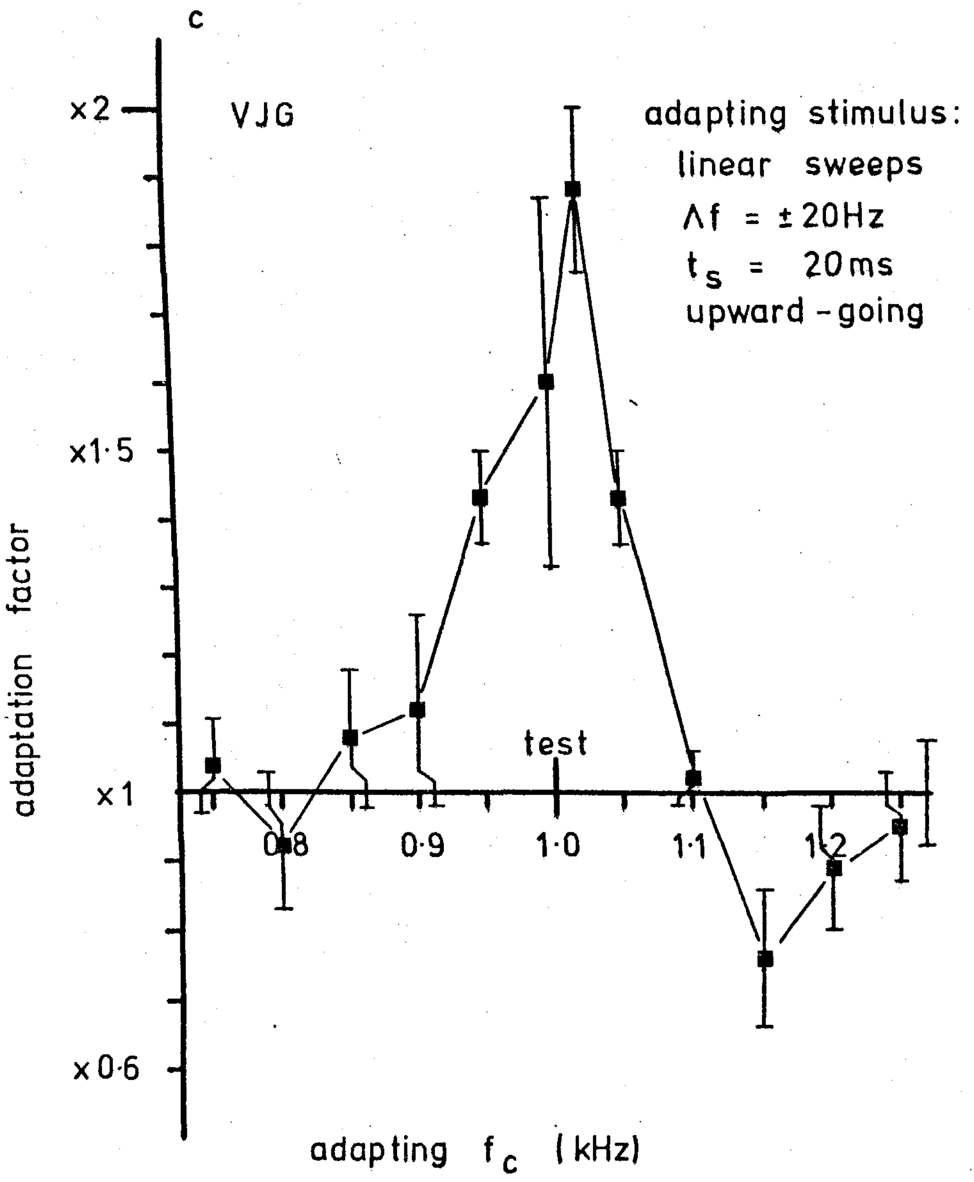

c
VJG
adapting stimulus:
linear sweeps
Λf = ±20Hz
t_s = 20ms
upward-going
adaptation factor
x2
x1·5
x1
x0·6
test
0·8
0·9
1·0
1·1
1·2
adapting f_c (kHz)

Fig. 4.2

stimulus must, in some way, reduce this activity. This would produce a threshold elevation where an increase in test-stimulus frequency-deviation is necessary to increase activity in the channel to threshold level. The results here show the opposite effect, a facilitation of threshold such that smaller test modulations induce the threshold activity level within the channel. The maximum facilitation factor is less than the maximum adaptation factor and has a narrower bandwidth. What is the basis of this facilitation effect? From the frequency extent (bandwidth and centre frequencies) it would seem to be related to the lateral inhibition suggested in the Chapter 3 data. In these experiments, activation of inhibition by adapting sweeps produces a fall in adaptation factor even though the portion of the sweep within the filter represents the optimal adapting stimulus for that channel. Adaptation was assumed to be a function of the induced activity in the FM system which could be reduced by inhibition at the frequency-selective stage of FM processing. The temporal separation of the inhibitory and "excitatory" effects would be small and the resultant, reduced, activity would determine the measured adaptation factor. The inhibitory influences must decay before the test phase of the stimulus cycle because any residual inhibition would also elevate thresholds by reducing test induced activity. The "excitatory" activity within the system which somehow determines adaptation and the inhibitory influences which affect this activity have different time courses, the adapting activity persisting to affect the detectability of the test modulation. If inhibition does not persist how could it produce facilitation? It might be possible that a background activity is present in the FM system acting to bias thresholds upwards through a small adaptation effect. Thus unadapted thresholds would be slightly adapted thresholds. Activation of the lateral inhibitory sidebands by small sweeps might reduce any background activity in the tuned channel increasing the detectability of the test modulation. This would be analogous to the phenomenon of unmasking (Shannon, 1976; Terry and Moore, 1977) (see App. D)

That inhibition is only present on the high-frequency side of the curve may be due to:

1. Larger inhibitory side-bands on the high-frequency side of the filter.
2. The direction of frequency sweep, i.e. with upward sweeps the high-frequency inhibitory area is activated after the excitatory region increasing the former's apparent effectiveness at certain values of adapting centre frequency.

4.4 Summary and Discussion

Tuning-curves for carrier-frequency measured by the method described by Kay and Matthews (1972) for both sinusoidal and linear sweep FM have bandwidths narrower than corresponding measures of the frequency selectivity of FM adaptation from Chapter 3. The shape of the curves differ significantly from those predicted from the Chapter 3 data and model without inhibitory influences, thereby suggesting the presence of these influences. From the shape of the curves, these influences appear to be present in frequencies closer to the test frequency than would be predicted from Chapter 3. This suggests some overlap of "excitatory" and inhibitory areas hidden in the Chapter 3 experiments.

At 0.25 and 1.0 kHz tuning curves were determined for three values of ±ΔF. Though estimates of bandwidth (Table 4.2) varied with this parameter, no systematic variation was observable. The adapting frequency deviation did determine the level of adaptation near the test frequency. The fact that adapting frequency deviation did not influence bandwidth systematically may reflect the presence of a constant inhibitory to "excitatory" ratio for each value of frequency deviation at a particular frequency.

Evidence for lateral inhibition was demonstrated with small linear frequency sweeps. This took the form of threshold facilitation on the high-frequency side of the tuning-curve consistent with the data and model of Chapter 3 but involving the concept of background adapting activity in FM channels. The inhibitory effects are analogous to the suppression effects demonstrated in masking experiments (Houtgast, 1971; Shannon, 1976; Houtgast, 1977; Terry and Moore, 1977). This inhibition could sharpen the tuned response of the FM processing system to carrier (centre)-frequency. The bandwidths and filter shapes of Chapter 3 can be regarded as a direct measure of the frequency selective properties of a particular channel, that is, one tuned to a specific frequency. Tuning curves represent complex interactions between the properties of this selectivity and reflect the selectivity of FM adaptation rather than FM channels per se. They demonstrate the functional aspects of this selectivity in the form of a sharpening around the test frequency enhancing the ability to discriminate between FM signals of different centre-frequency.

Inhibition also helps tune the channel response to frequency deviation such that an optimal range occurs (the PMV of Chapter 3). Thus sweeps below the PMV and larger than PMV sweeps are indistinguishable in terms of induced activity within a single channel though the distributed activity across an array of channels could code this variable. Indeed, this limit imposed upon the frequency deviation of sweeps can be regarded as a by-product of frequency selectivity which is unlikely to represent the only mechanism coding frequency deviation. Hartman (1977) reports experiments suggesting three separate mechanisms in FM width perception. Further, some formant transitions exceed the PMV values measured in Chapter 3 (Lehiste and Peterson, 1961) suggesting the "tuning" to frequency deviation has no functional role in the coding of formant transitions.

Though not necessarily FM-specific in the sense that the elements of the channel are concerned only with FM, the selectivity studied above represents one stage in the processing of these stimuli below the level of detection of the test stimulus. The frequency selectivity represents the range and strength of FM carrier-frequencies having access to a specific tuned channel signalling the value of one dimension of the test stimulus upon which detection is based. The frequency selectivity is probably based on peripheral frequency selectivity (Evans, 1975) with the initial input to the FM stage an array of frequency-tuned channels (fibres). No marked asymmetry was found.

TABLE 4.1

Values of mean adaptation and standard deviation from all sinusoidal FM experimental conditions

F_c (TEST) = 0.25 kHz							F_c (TEST) = 0.5 kHz			F_c (TEST) = 1.0 kHz RBG						
Adapting F_c (kHz)	ΔF = ±32.5 Hz		ΔF = ±50 Hz		ΔF = ±100 Hz		Adapting F_c	ΔF = ±70 Hz		Adapting F_c (kHz)	ΔF = ±40 Hz		ΔF= ±90 Hz		ΔF = ±160 Hz	
	AF	SD	AF	SD	AF	SD		AF	SD		AF	SD	AF	SD	AF	SD
0.125			1.15	0.06			0.35	1.52	0.13	0.75	1.26	0.08	1.14	0.08		
0.15	1.23	0.07	1.37	0.07	1.41	0.11	0.4	1.83	0.11	0.8					1.16	0.06
0.175	1.44	0.09					0.45	1.99	0.04	0.85	1.15	0.08	0.11			
0.2	1.47	0.1	1.61	0.19	1.68	0.07	0.5	3.17	0.21	0.9	1.23	0.13	1.45	0.06	1.63	0.11
0.225	1.92	0.17	2.18	0.12	2.11	0.26	0.55	1.66	0.06	0.95	1.35	0.13	2.11	0.17	1.71	0.18
0.25	2.55	0.1	3.25	0.115	1.87	0.1	0.6	1.68	0.08	1.0	1.87	0.24	2.87	0.25	2.06	0.12
0.275	2.14	0.11	1.81	0.11	1.92	0.08	0.65	1.18	0.11	1.05	1.18	0.09	2.55	0.12	1.59	0.09
0.3	1.32	0.06	1.32	0.06	1.45	0.03				1.1	1.26	0.17	1.63	0.05	1.29	0.08
0.325	1.08	0.12								1.15	1.19	0.09	1.3	0.11		
0.35			1.17	0.16	1.1	0.11				1.2					1.11	0.06

TABLE 4.1 (Cont)

F_c (TEST) = 1.0 kHz VJG						
Adapting F_c (kHz)	ΔF = ±40 Hz		ΔF= ±80 Hz		ΔF = ±160 Hz	
	AF	SD	AF	SD	AF	SD
0.75			1.15	0.11		
0.8						
0.85	1.06	0.1	1.34	0.13	1.17	0.13
0.9	1.41	0.14	1.73	0.15	1.04	0.07
0.95	1.3	0.07	2.55	0.1	1.64	0.1
1.0	1.97	0.14	3.43	0.11	1.69	0.07
1.025	2.51	0.13				
1.05	2.32	0.1	1.95	0.07	1.12	0.25
1.1	1.29	0.11	1.38	0.09	1.02	0.04
1.15			1.32	0.08		
1.2	1.06	0.13				
1.25			1.44	0.19		

F_c (TEST) = 4.5 kHz		
Adapting F_c (kHz)	ΔF = ±350 Hz	
	AF	SD
4.0	1.34	0.06
4.2	1.84	0.09
4.3	2.44	0.12
4.4	3.06	0.36
4.5	3.56	0.15
4.6	2.51	0.13
4.7	1.9	0.06
4.8	1.95	0.07
5.0	1.43	0.12

TABLE 4.2

F_c (kHz)	±ΔF (Hz)	Bandwidth Chap.4 (Hz)	Bandwidth Chap.3 (Hz)
0.25	32.5 50 100	65 48 115	100
0.5	70	70	140
1.0	40 90 160	70 140 180	180
1.0 (VJG)	40 80 160	93 113 106	160
4.5	350	360	700

Table showing half-height bandwidths from sinusoidal-FM tuning curves with Chapter 3 Gaussian bandwidths for comparison.

CHAPTER 5

5.1 Introduction

This chapter attempts to determine the mechanism of adaptation using a psycho-physical technique described by Dealy and Tolhurst (1974) in a paper entitled "Is spatial adaptation an after-effect of prolonged inhibition?"

The paper discusses two separate models for interactions between spatial-frequency tuned channels, that is, for the effect of one spatial-frequency upon another as described by tuning-curves (e.g. see Blakemore and Campbell, 1969). The first proposes adaptation is an after-effect of prolonged excitation of the channel and that tuning-curves represent the sensitivity of the channel to a range of input frequencies. A tuning-curve can be regarded as an inverted threshold curve where greater adaptation implies a lower threshold. For auditory tuning-curves tuned, for example, to modulation-frequencies of 8 and 10 Hz, differences in adaptation produced by an 8 Hz adaptor at these two test frequencies would reflect the different sensitivities of the two channels to an 8 Hz stimulus. Obviously the 8 Hz channel would be more sensitive to the 8 Hz adaptor than would the 10 Hz channel and would be more adapted. The excitation model would predict that the 8 Hz channel responds when the 8 Hz adaptors "strength" exceeds the channels threshold for that frequency. Because the 10 Hz channel is less sensitive to an 8 Hz stimulus the adaptor "strength" would have to be higher in order to activate and adapt the channel. If for "strength" we substitute adapting frequency-deviation then adaptation of the 10 Hz channel by the 8 Hz stimulus would be expected to occur at a higher adapting frequency-deviation than adaptation of the 8 Hz channel.

The second model proposes adaptation is an after-effect of prolonged inhibition between channels. Thus the effect of an 8 Hz adapting-stimulus upon the 10 Hz channel comes via a lateral-inhibitory connection. The effect of 8 Hz upon the 8 Hz channel comes from self-inhibition and, possibly, inhibition from surrounding channels activated by the adapting stimulus. This model would predict that adaptation of the 10 Hz channel by the 8 Hz adapting stimulus would begin at the same adapting frequency-deviation as adaptation of the 8 Hz channel because lateral-inhibitory activity would be initiated as soon as the 8 Hz channel was activated. In other words, adaptation of the 8 and 10 Hz channels would begin as soon as the adapting-frequency deviation exceeded threshold. Tuning-curves would, in these terms, represent the range and strength of adapting lateral-inhibitory connections between channels rather than the range of inputs to the channel. The strength of inhibition is assumed to diminish as the distance between test and adapting frequency increases. Figure 5.1 (Fig. 2 of Dealy and Tolhurst, 1974) illustrates the experimental rationale and predictions. For adapting contrast substitute adapting frequency-deviation.

The experiments determine both the mechanism of adaptation and the nature of the interactions reflected in tuning-curves. In Chapters 3 and 4, tentative models were assumed where adaptation was a consequence of excitation. Lateral inhibitory effects seemed to reduce this excitation and thus reduce adaptation. Further, the inhibition did not seem to be of sufficient duration to affect the test stimulus directly whereas the after-effect of excitation did persist; neither was it clear whether adaptation occurred "somewhere else" in the system or at the level of carrier-frequency selective channels.

The assumptions of earlier chapters are tested directly in this chapter which also provides clues to the locus of adaptation. Experiments were carried out for two separate dimensions of sinusoidal-FM, modulation-frequency and carrier-frequency.

Fig. 5.1. From Dealy and Tolhurst (1974) p.265. Explanation and prediction of excitation and inhibition models.

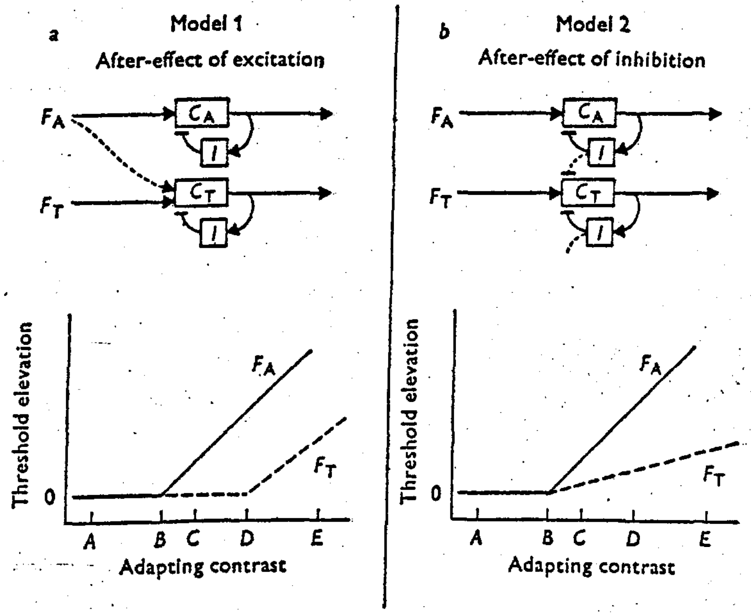


Fig. 2. Two models of the mechanism of spatial adaptation. *a*, on the left, it is suggested that adaptation arises from prolonged excitation. Frequency F_A excites channel C_A well and also excites channel C_T to some extent. The two channels become adapted to a degree dependent on how much they are excited by the adapting grating. The boxes labelled *I* represent the adaptation mechanism and do not necessarily represent inhibitory inter-neurones. The lower part of the left-hand Figure shows the threshold elevation curves expected for the test frequencies F_A and F_T after adapting to F_A. The points *A*, *B*, *C*, *D* and *E* are the reference contrasts in Fig. 1. *b*, on the right it is supposed that adaptation arises from prolonged inhibition. Channel C_T may not be excited by frequency F_A, but it may be inhibited by channel C_A which does, of course, respond to frequency F_A. Channel C_T will become adapted to a degree dependent on how much channel C_A is excited by the adapting grating. The lower part of the right-hand Figure shows the elevation curves expected on this hypothesis.

5.2 Determination of tuning curves

5.2.1 Methods

Two experiments with sinusoidal-FM test- and adapting-stimuli were carried out as follows:

(1) Modulation-frequency tuning-curves were determined by holding the test-frequency constant and varying the adapting-frequency (see Kay and Matthews, 1972, for examples of curves at 0.25 kHz). The adapting frequency-deviation was held constant at the PMV of the centre-frequencies used, 0.25 and 1.0 kHz for RBG, 1.0 kHz for VJG. PMV values can be found in Table 3.2. Tuning-curves were determined at test-frequencies of 8 and 10 Hz for RBG at both centre-frequencies. Curves at 8 and 12 Hz were determined for VJG. Most data points at 0.25 kHz (RBG) were the means of two threshold estimates except the 6, 8 and 10 Hz adapting conditions of the 8 Hz curve where 6 estimates were made. For all other data points 3 estimates were made and means and standard deviations calculated.

(2) Carrier (centre)-frequency tuning-curves were determined for a test-frequency of 1.05 kHz for both subjects by the methods described in Chapter 4. Adapting frequency-deviations were ±90 Hz and ±80 Hz for RBG and VJG respectively. Modulation-frequencies were held constant at 8 Hz. All data points are the means of 3 threshold estimates. Standard deviations were calculated.

5.2.2 Results and discussion

(1) Modulation-frequency curves: Data are shown in Fig. 5.2a-c. Marked tuning is found confirming the results of Kay and Matthews (1972). Threshold facilitation is found in all curves especially at 1.0 kHz. Within the terms of the model proposed for carrier-frequency curves in Chapter 4, this is evidence for lateral-inhibition. Facilitation is discussed later within the context of an improved model. It is worth noting that facilitation was found but not discussed by Kay and Matthews (1972). The curves at 1.0 kHz also have narrower bandwidths than the 0.25 kHz curves suggesting

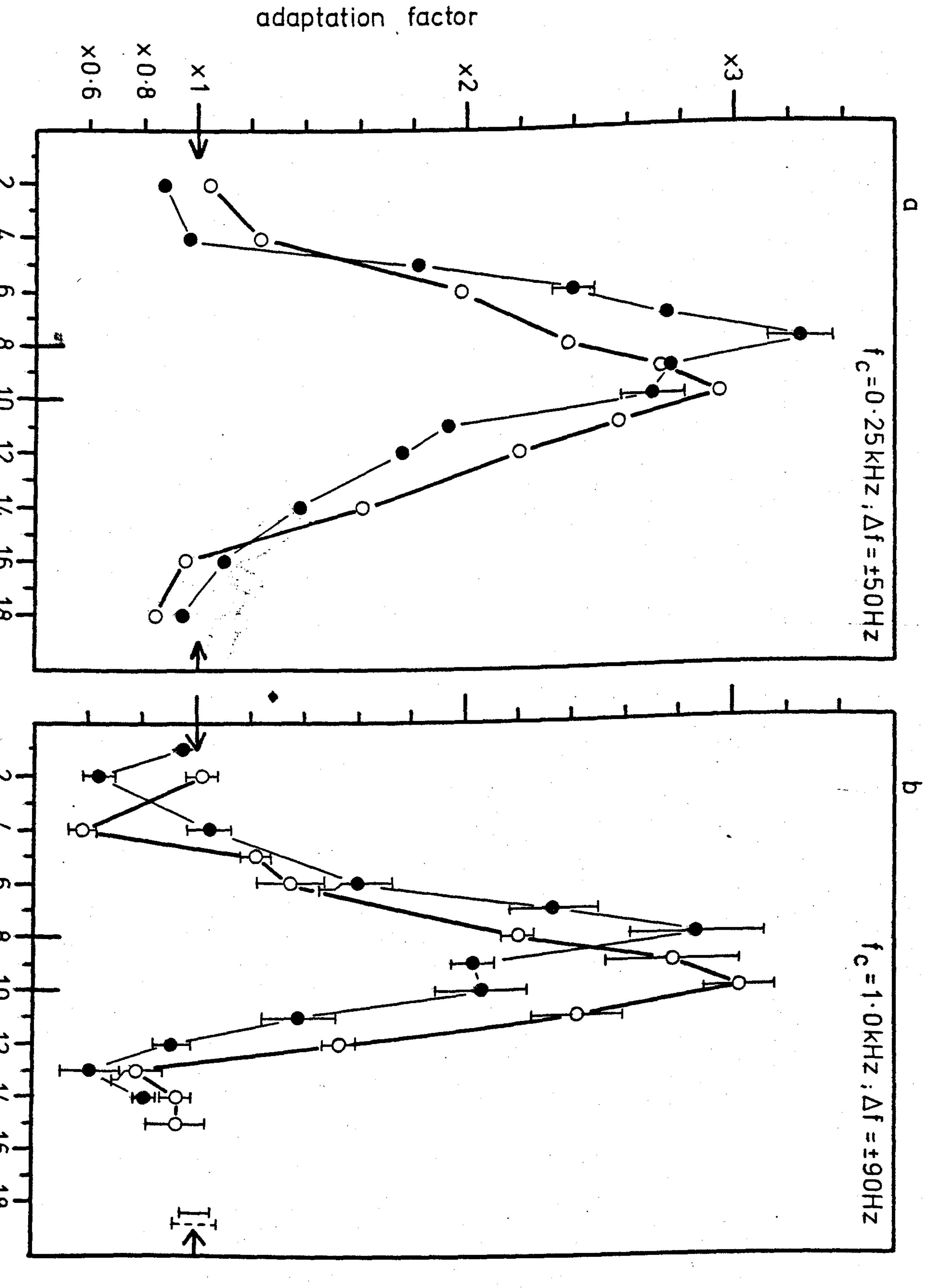
Fig. 5.2a-c. Modulation-frequency (f_m) tuning-curves.

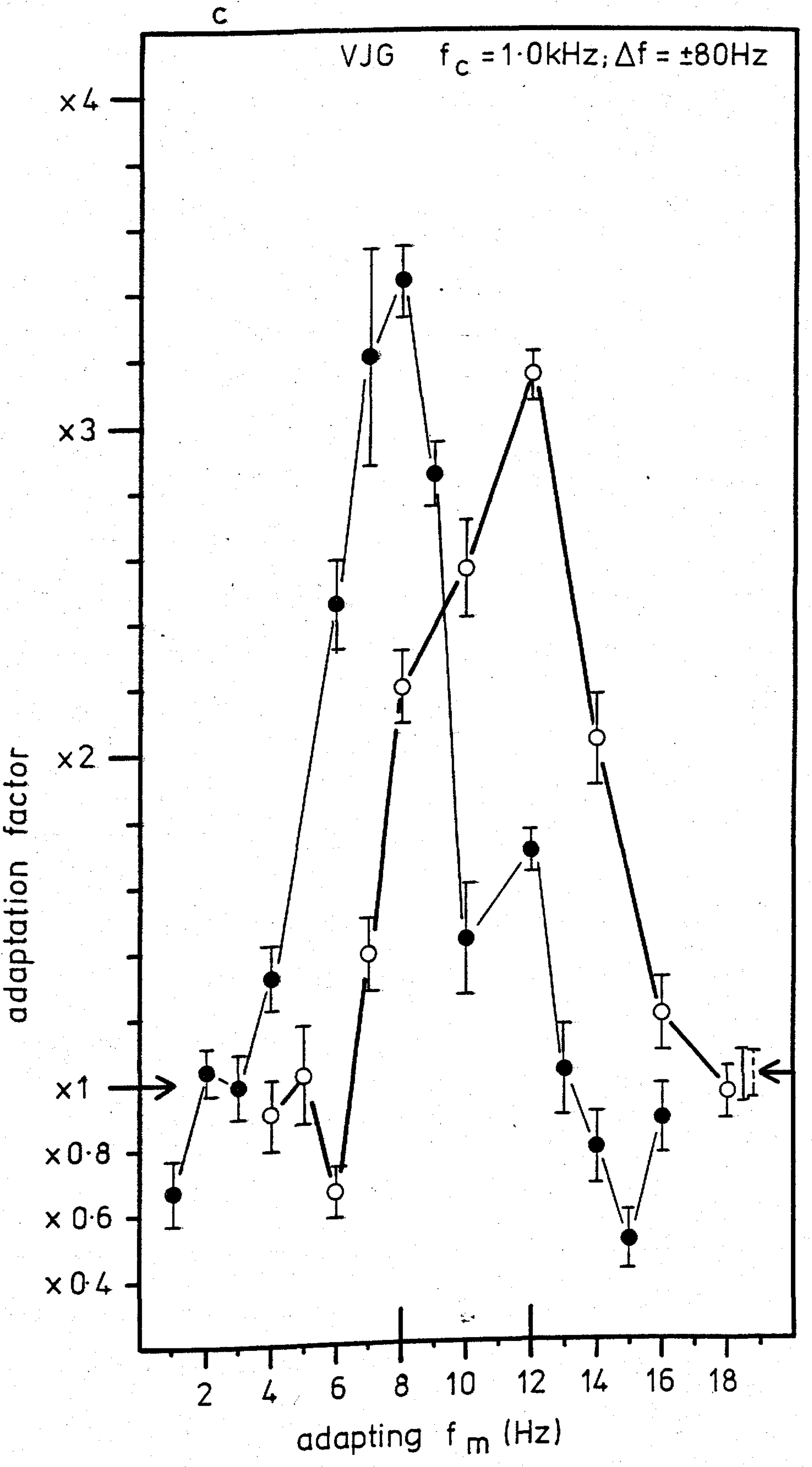
(a) RBG, 0.25 kHz; 8 Hz test (closed circles, thin lines); 10 Hz (open circles, thick lines).

(b) RBG, 1.0 kHz; 8 Hz test and 10 Hz test, key as above.

(c) VJG, 1.0 kHz, 8 Hz test (closed circles, thin lines); 12 Hz test (open circles, thick lines).

All stimuli were sinusoidal-FM. Vertical bars on the left of 1.0 kHz curves are standard deviations of unadapted thresholds expressed as adaptation factor.


adaptation factor
x3
x2
x1
x0·8
x0·6
a
f_c=0·25kHz ; Δf=±50Hz
b
f_c=1·0kHz ; Δf=±90Hz
2
4
6
8
10
12
14
16
18
adapting f_m (Hz)


c
VJG $f_c = 1{\cdot}0$kHz; $\Delta f = \pm 80$Hz
adaptation factor
x4
x3
x2
x1
x0·8
x0·6
x0·4
2
4
6
8
10
12
14
16
18
adapting f_m (Hz)

the need to differentiate between modulation-frequencies is greater at 1.0 kHz. What is important for the present is the overlap between the curves allowing the choice of test- and adapting-frequencies for later experiments where plots of adaptation as a function of adapting frequency-deviation are made where adapting and test frequencies are either equal or different (see Fig. 5.1). For RBG, 8 Hz was chosen as the adapting-frequency and 8 and 10 Hz as the test frequencies. The tuning-curves obviously validate this choice. The curve for the 8 Hz test was reported in Chapter 3. The modulation-frequencies chosen were the same for 0.25 and 1.0 kHz. For VJG (1.0 kHz) the adapting-frequency was 8 Hz and the tests 8 Hz and 12 Hz. Once again the 8 Hz test curve was reported in Chapter 3.

(2) Carrier-frequency curves: Curves for 1.05 kHz together with 1.0 kHz curves (with the same adapting frequency-deviation) from Chapter 4 are shown in the left-hand graphs of Fig.5.4a-b. From these curves the adapting (1.0 kHz) and test frequencies (1.0 and 1.05 kHz) were chosen.

5.3 Adaptation as a function of adapting frequency-deviation: adaptation as an after-effect of prolonged inhibition

5.3.1 Methods

(1) Modulation-frequency. Plots of adaptation as a function of adapting frequency-deviation were determined with sinusoidal-FM test- and adapting-stimuli where:

(a) the modulation-frequency of the test and adapting stimuli were equal at 8 Hz. This was true for 0.25 and 1.0 kHz and both subjects (see Chapter 3),

(b) test- and adapting-frequencies differed.

Test values were 10 Hz for RBG at both 0.25 and 1.0 kHz and 12 Hz for VJG (1.0 kHz). The adapting-frequency was 8 Hz. The two conditions act as a test for the inhibition model for channels tuned to modulation-frequency. A further condition involved the reversal of the test- and adapting-frequencies of condition (b). The carrier-frequency was held constant throughout the experiments at either 0.25 or 1.0 kHz.

(2) Carrier-Frequency. Plots of adaptation as a function of adapting frequency deviation were determined with sinusoidal-FM stimuli where:

(a) test- and adapting-carrier-frequencies were equal at 1.0 kHz. This is the same function as the 1.0 kHz function of condition (a) above, i.e. from Chapter 3,

(b) the test-frequency was 1.05 kHz and the adapting-frequency 1.0 kHz. The modulation-frequency was held constant at 8 Hz in both conditions.

The two conditions act as a test for the inhibition model for channels tuned to carrier-frequency.

Three threshold estimates were made for each data point and means and standard deviation calculated.

5.3.2 Results and discussion

Functions from the modulation-frequency conditions are shown in Fig. 5.3a-c and those from the carrier-frequency conditions in the right-hand graphs of Fig. 5.4a-b. In most of the 1.0 kHz curves an extra data point at an adapting frequency-deviation of ±10 Hz was included. This value was not used in the Chapter 3 experiments. The condition in the modulation-frequency experiments in which the differing test and adapting frequencies were reversed was included even though a function where test and adapting frequencies were equal to the adapting-frequency of this condition (10 Hz for RBG, 12 Hz for VJG) would ideally be required for comparison. It was felt that this condition would provide useful corroborative evidence without the comparison.

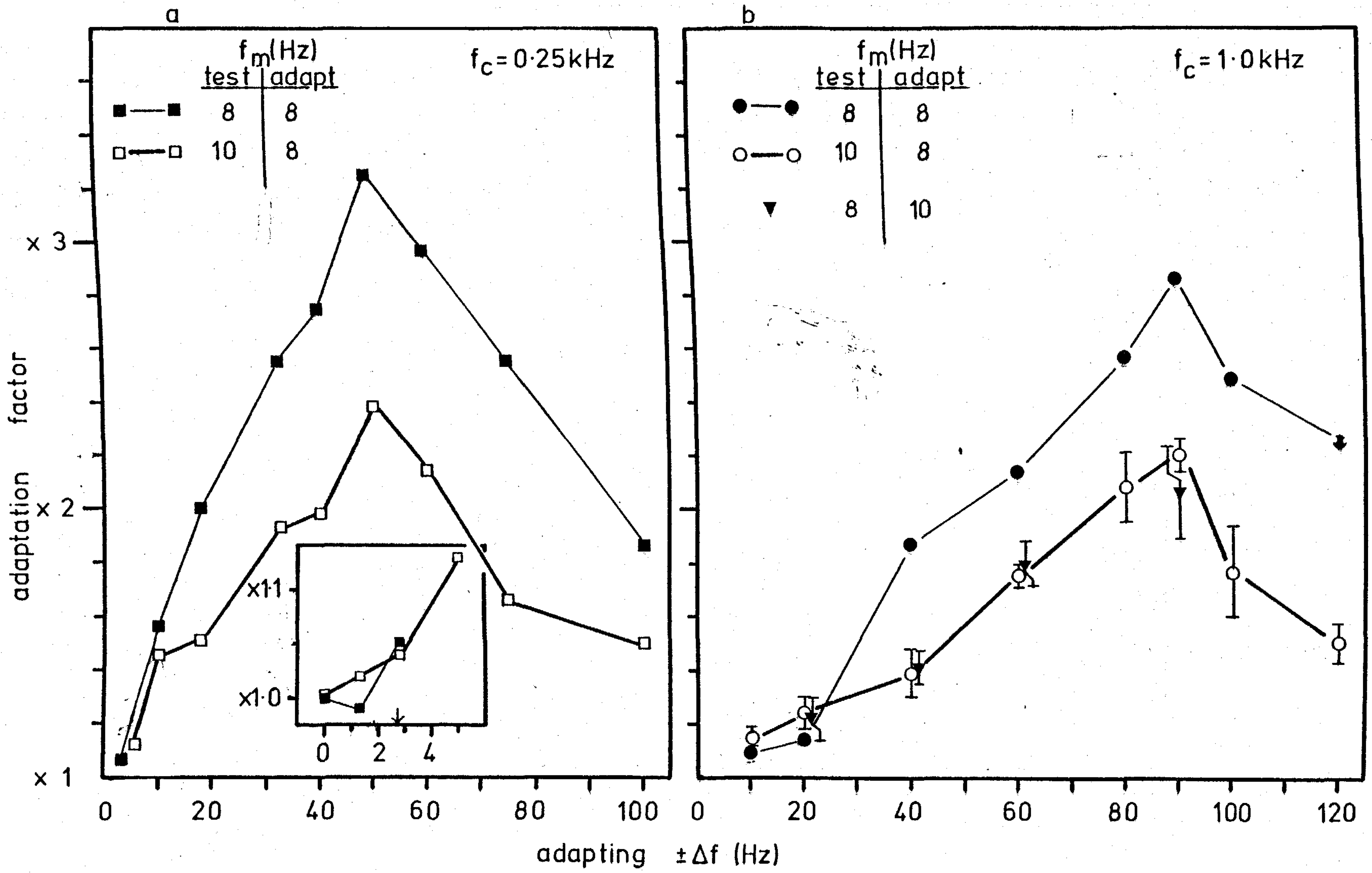
At first sight the results seem to confirm the inhibition hypothesis in that the different functions seem to converge on the same point especially if straight lines are fitted by eye. However, a major impediment to accepting this conclusion at 1.0 kHz is the fact that the smallest frequency-deviation used (±10 Hz) is of the order of ten times the unadapted threshold at this frequency. The scale might be too large

Fig. 5.3a-c. Plots of adaptation as a function of adapting frequency-deviation (±ΔF).

(a) RBG, 0.25 kHz; test and adapting-f_m equal to 8 Hz (closed squares, thin lines); test f_m = 10 Hz, adapting f_m = 8 Hz (open squares, thick lines). Inset shows functions for small values of adapting ±ΔF.

(b) RBG, 1.0 kHz; test and adapting f_m = 8 Hz (closed circles, thin line); test f_m = 10 Hz, adapting f_m = 8 Hz (open circles, thick line); test f_m = 8 Hz, adapting f_m = 10 Hz (triangles).

(c) VJG, 1.0 kHz; test and adapting f_m = 8 Hz (closed squares); test f_m = 12 Hz, adapting f_m = 8 Hz (open circles); test f_m = 8 Hz, adapting f_m = 12 Hz (triangles).



a
f_m(Hz)
test | adapt
■—■ 8 8
□—□ 10 8
f_c=0·25kHz
adaptation factor
x 1
x 2
x 3
x1·0
x1·1
0
2
4
0
20
40
60
80
100
b
f_m(Hz)
test | adapt
●—● 8 8
○—○ 10 8
▼ 8 10
f_c=1·0kHz
0
20
40
60
80
100
120
adapting ±Δf (Hz)

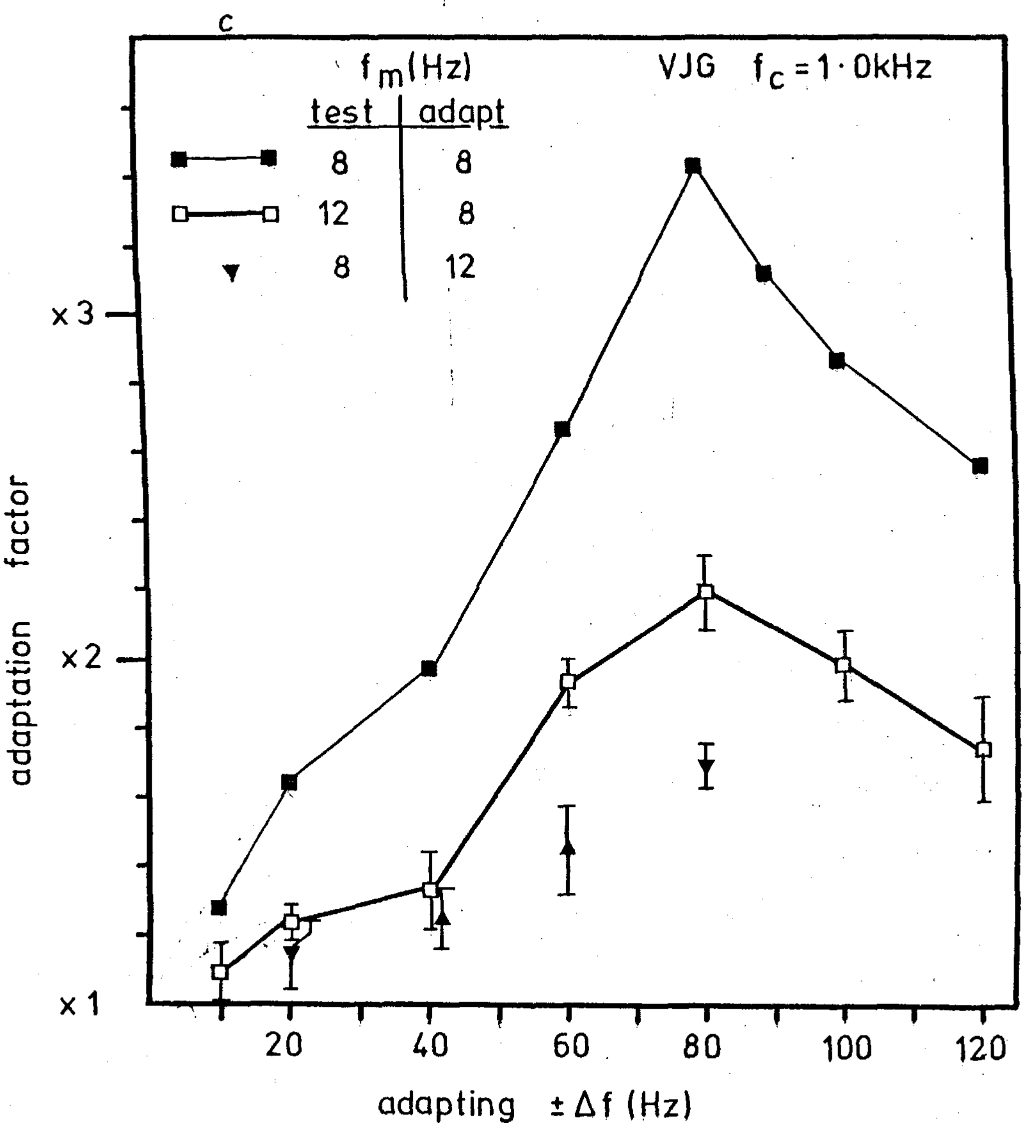
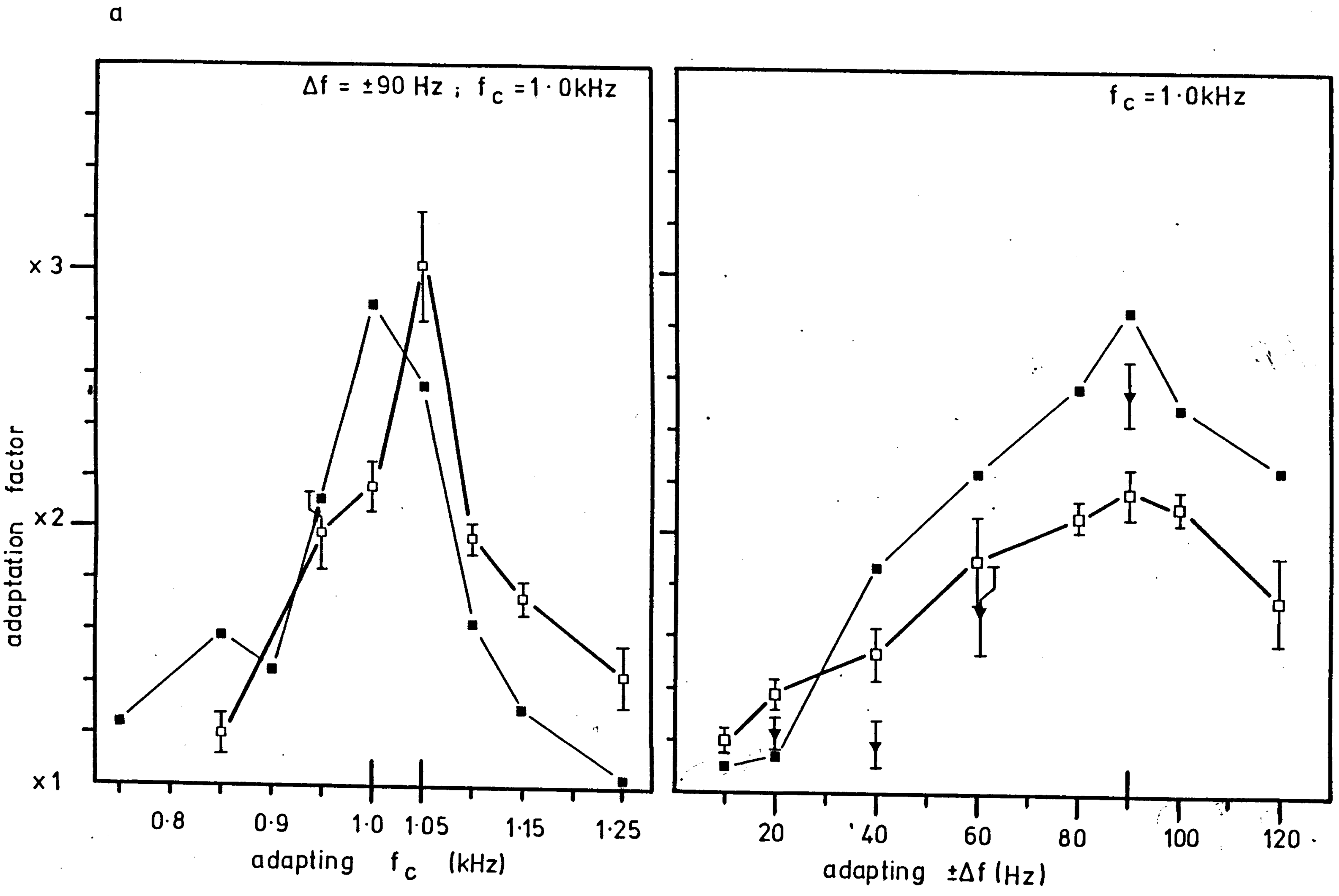
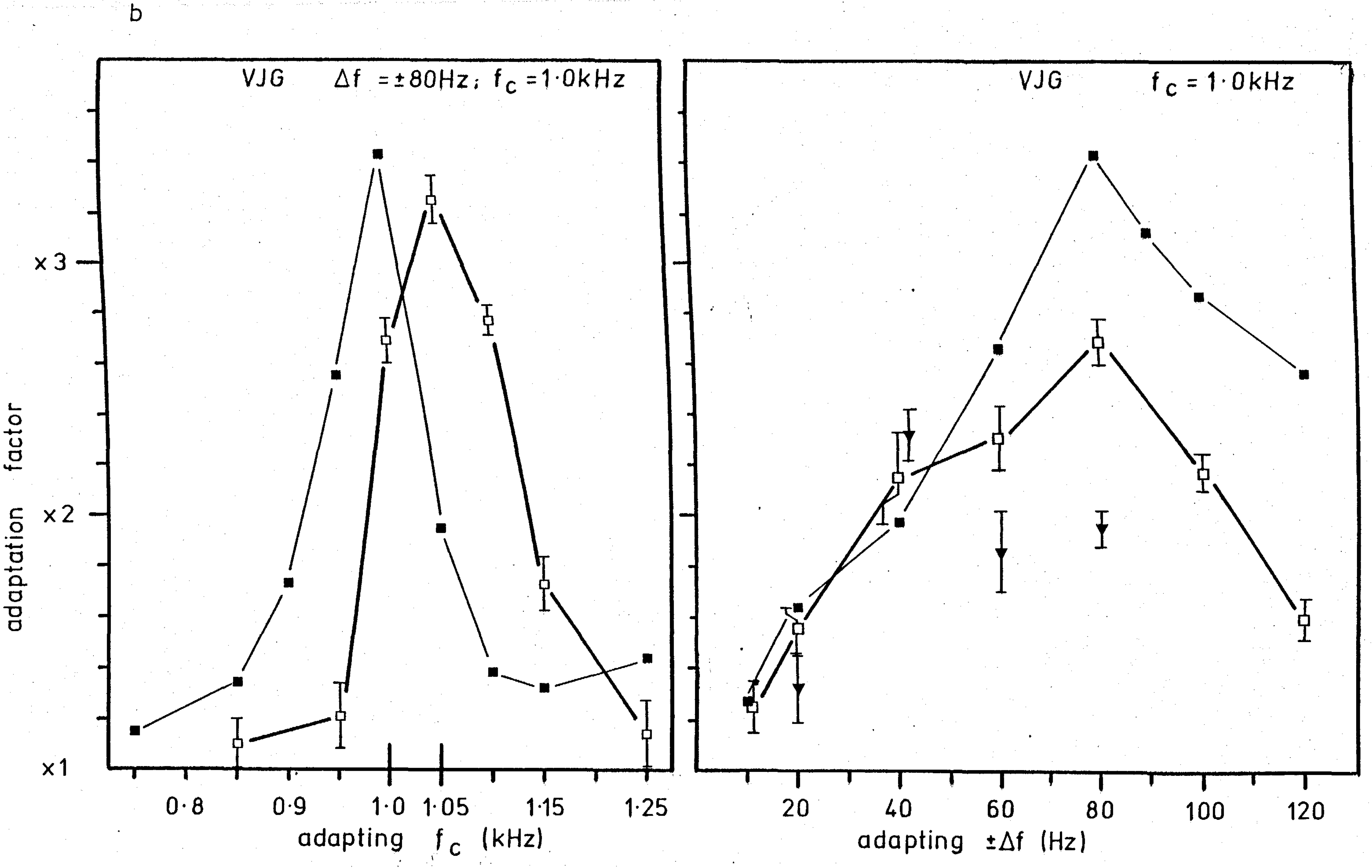

c
f_m (Hz)
test | adapt
8 | 8
12 | 8
8 | 12
VJG f_c = 1·0kHz
x 3
x 2
x 1
adaptation factor
20
40
60
80
100
120
adapting ± Δf (Hz)

Fig. 5.4a-b. Left-hand graphs show f_c tuning-curves at 1.0 and 1.05 kHz. Right-hand graphs show plots of adaptation versus adapting ±ΔF where: test and adapting f_c = 1.0 kHz (filled squares); test f_c = 1.05 kHz, adapting f_c = 1.0 kHz (open squares); test f_c = 1.0 kHz, adapting f_c = 1.05 kHz (triangles).

(a) RBG (b) VJG


a
Δf = ±90 Hz ; f c =1·0kHz
f c =1·0kHz
adaptation factor
x 3
x 2
x 1
0·8
0·9
1·0
1·05
1·15
1·25
adapting f c (kHz)
20
40
60
80
100
120
adapting ±Δf (Hz)


b
VJG Δf = ±80Hz; fc = 1·0kHz
adaptation factor
x 3
x 2
x 1
0·8
0·9
1·0
1·05
1·15
1·25
adapting fc (kHz)
VJG fc = 1·0kHz
20
40
60
80
100
120
adapting ±Δf (Hz)

to reveal the critical area of convergence around the threshold values of adapting frequency deviation. For this reason further experiments were carried out at a later date with smaller frequency-deviations. This was not necessary at 0.25 kHz because small enough frequency-deviations relative to the unadapted threshold had been used (see the inset of Fig. 5.3a where the vertical arrow gives the unadapted threshold for the 8 Hz adapting stimulus). The hypothesis and model of adaptation as an after-effect of inhibition is thus confirmed at 0.25 kHz.

5.4 Data from small adapting-frequency-deviations

5.4.1 Methods

The experiments were identical to those described above for the main 1.0 kHz modulation- and carrier-frequency conditions. Three threshold estimates were made at each data point.

5.4.2 Results and discussion

Fig. 5.5a-b shows plots of adapted threshold as a function of adapting frequency-deviation. The vertical arrow on the figure points to the unadapted threshold of the adapting stimulus, i.e. the point at which adaptation would be expected to begin in each of the conditions. Adapted threshold was used because this gives a more precise description of the influence of the adaptor or the differing thresholds of the three conditions. These conditions are:

(1) Modulation- and carrier-frequencies, 8 Hz and 1.0 kHz respectively, equal for both test- and adapting-stimuli (closed circles, solid lines of Fig. 5.5).

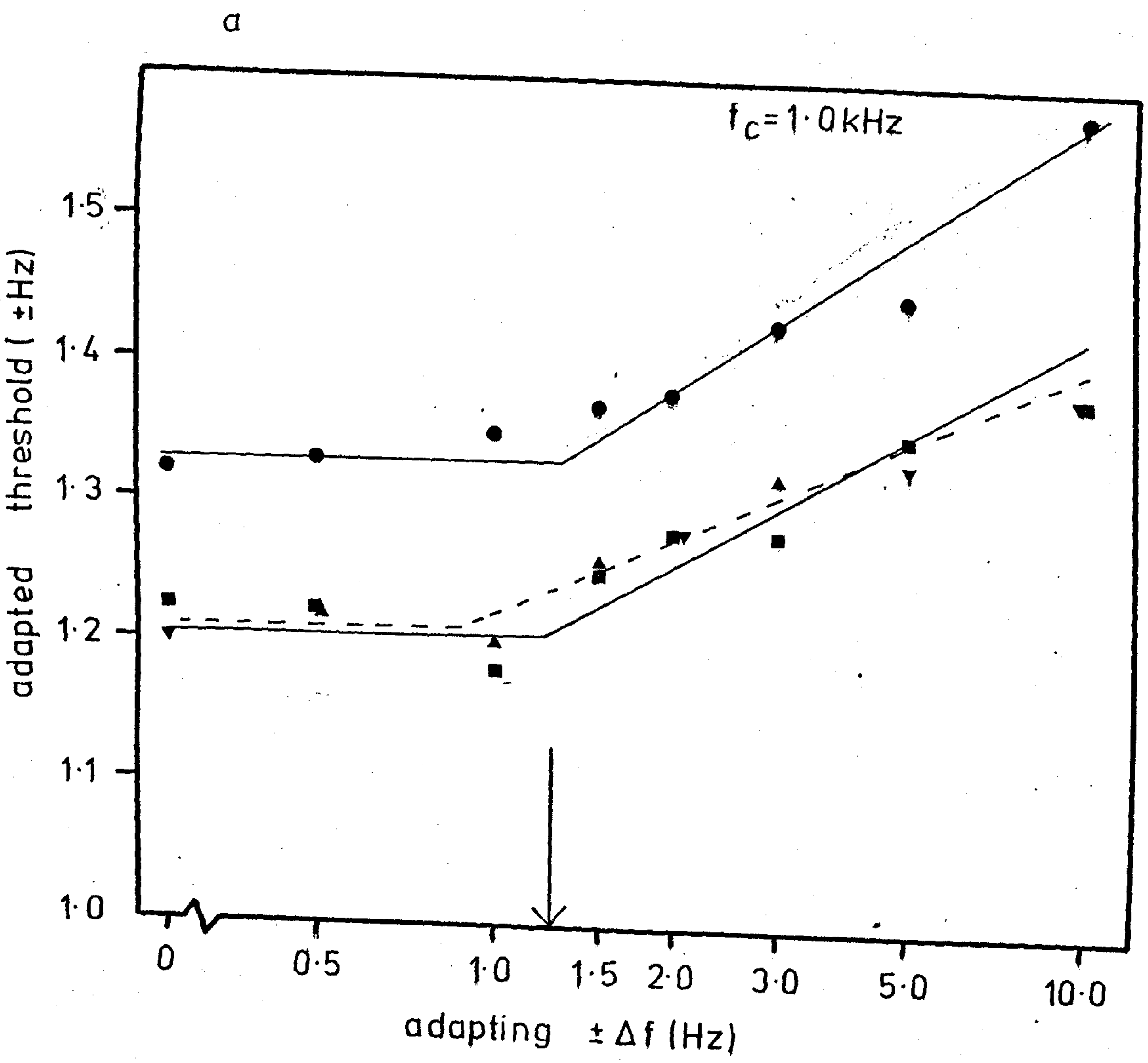
(2) Test- and adapting-carrier-frequency constant at 1.0 kHz, test modulation-frequency equalto 10 Hz (12 Hz for VJG), adapting frequency equal to 8 Hz (closed squares, solid lines of Fig. 5.5).

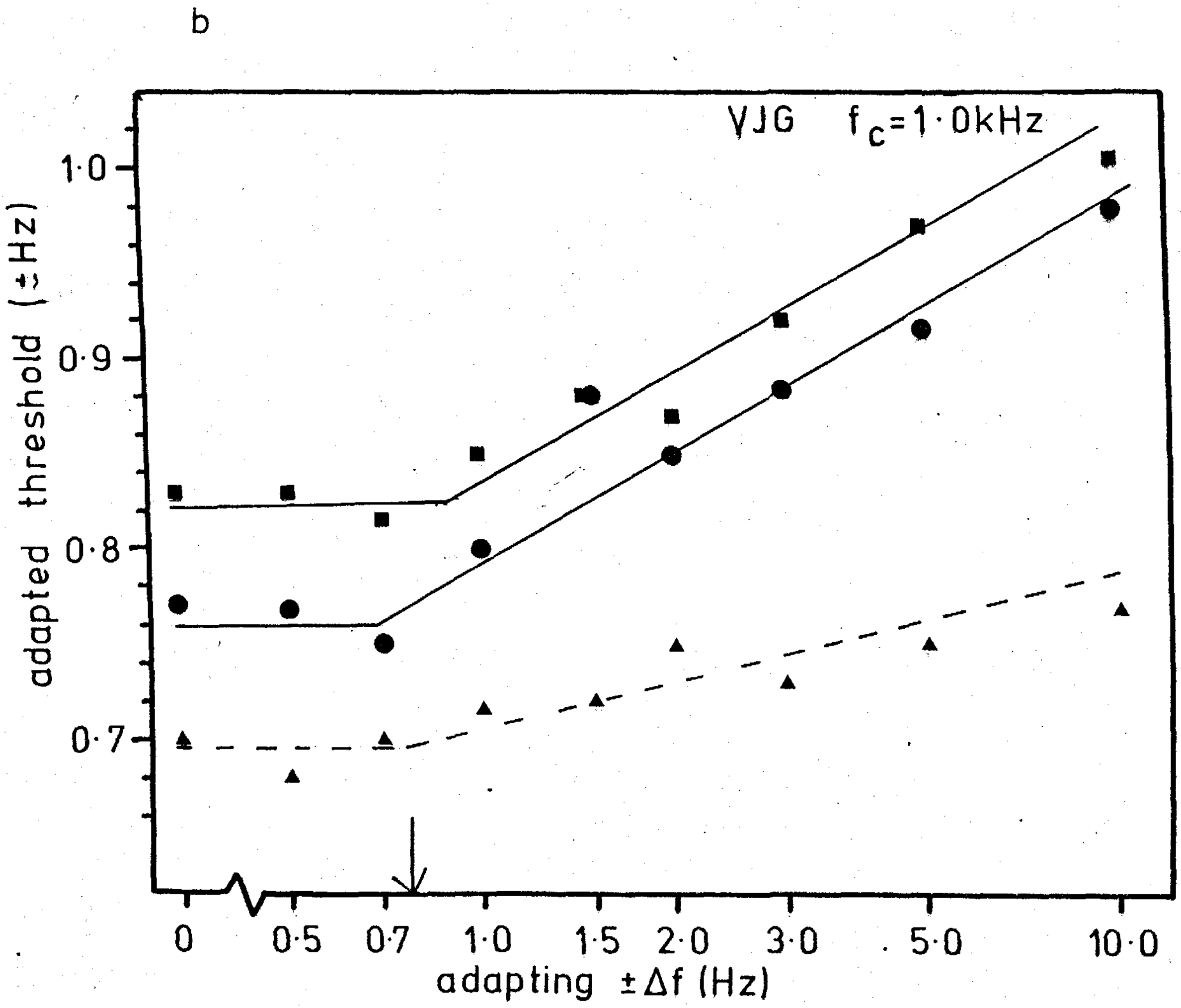
(3) Modulation-frequency of test and adapting stimulus constant

Fig. 5.5a-b. Plots of adapted threshold versus adapting ±ΔF for small values of ±ΔF where:

(a) RBG, test and adapting f_c = 1.0 kHz, f_m = 8 Hz (closed squares); test f_c = 1.05 kHz, adapting f_c = 1.0 kHz, f_m = 8 Hz, f_c = 1.0 kHz (triangles, dashed lines).

(b) VJG, test and adapting f_c = 1.0 kHz, f_m = 8 Hz (closed circles); test f_c = 1.05 kHz, adapting f_c = 1.0 kHz, f_m = 8 Hz (closed squares; test f_m = 12 Hz, adapting f_m = 8 Hz, f_c = 1.0 kHz (triangles, dashed line).


a
f_c=1·0kHz
adapted threshold (±Hz)
1·0
1·1
1·2
1·3
1·4
1·5
0
0·5
1·0
1·5
2·0
3·0
5·0
10·0
adapting ±Δf (Hz)


b
VJG f_c=1·0kHz
adapted threshold (±Hz)
1·0
0·9
0·8
0·7
0
0·5
0·7
1·0
1·5
2·0
3·0
5·0
10·0
adapting ±Δf (Hz)

at 1.0 kHz, test carrier-frequency equal to 1.05 kHz, adapting carrier-frequency equal to 1.0 kHz (triangles, dashed line of Fig. 5.5).

Straight lines were fitted by eye to each of the functions. It can be seen that the thresholds in each of the functions begins to rise at or very near the point at which the adapting frequency-deviation exceeds threshold, i.e. the point at which it would be expected to activate its own channel and adapt surrounding channels via lateral-inhibitory connections. The validity of the inhibition model is confirmed at 1.0 kHz for both modulation-frequency and carrier-frequency tuned channels.

5.5 Discussion

The data are consistent with a model in which adaptation is an after-effect of prolonged inhibition. However, it is impossible to differentiate between lateral excitatory processes and lateral inhibitory processes by these experiments as both would generate the same predictions with respect to adaptation as a function of adapting frequency-deviation. If the lateral excitatory model was correct, excitatory inputs to the channels would also produce adaptation and tuning-curves would represent the interaction and lateral and input influences unless an additional factor were introduced by which only the lateral activity resulted in adaptation. Only one factor is present in the inhibitory models description of tuning-curves and adaptation and for this reason it remains the more attractive model. The implications of the inhibitory model for earlier data and models is discussed below.

(1) Tuning curves: These represent the frequency-range of channels adapting a test channel through lateral-inhibitory connections. As the distance between the test- and adapting-channels increases, the strength of inhibition diminishes. When test- and adapting-frequencies are equal adaptation can be effected through self-inhibition and/or inhibition from adjacent channels activated by the input stimulus. The shape of the tuning-

curve may reflect processes involved in facilitation discussed below. A single FM channel can be considered as being tuned to both carrier- and modulation-frequency.

(2) Threshold facilitation: This is found in both carrier-frequency (f_c) and modulation-frequency (f_m) tuning-curves and is the opposite process to adaptation. The concept of inhibition of background adapting activity was introduced in Chapter 4 to explain the phenomenon. Obviously this is now inadequate given that adaptation is a consequence of inhibition and that connections between channels are inhibitory. In the context of the inhibitory model, facilitation can be regarded as a release from adapting inhibition, that is, an inhibition of inhibition. Because the connections between channels have a limited range, more distant channels cannot reach the test-channel directly but could inhibit channels closer to the test thereby reducing their effect on the test channel. To account for facilitation this "releasing" inhibition must inhibit background activity in channels adjacent to the test channel. The bandwidths of facilitation effects are narrower than adapting bandwidths in both f_c and f_m tuning-curves. In f_c tuning-curves facilitation is only present with small frequency-deviations, presumably because these activate a small range of channels around the facilitating or "releasing" channels so that any adaptation present can be overridden by the "releasing" process. For f_m tuning-curves the input bandwidth might be such that except for a small frequency region the "releasing" effects, though present, are hidden by simultaneous adapting effects. The input bandwidth may determine which channels are activated but not the bandwidth of adaptation and "releasing" effects. "Releasing" effects might sharpen the tuning in a manner similar to that discussed in Chapter 4 for lateral inhibition in an excitatory model. The

(3) The role of frequency-deviation and the Gaussian filter of Chapter 3: The data of earlier chapters were discussed in terms of a model in which both the Gaussian curves of Chapter 3 and the F_c tuning-curves of Chapter 4 represented the range of carrier-frequencies exciting a channel and where adaptation was assumed to be an after-effect of this excitation. An attempt was made in Chapter 4 to explain the difference between Gaussian and tuning-curve bandwidths in terms of lateral-inhibitory processes. In Chapter 3 the level of adaptation of a single-tuned channel was shown to be a function of the frequency-deviation (±ΔF) of the adapting-stimulus. The activation of the channel and the resulting adaptation (now known to be due to self-inhibition and inhibition from adjacent channels) was adequately described by the area under the modulating-waveform within a Gaussian filter. After a certain value of ±ΔF, the PMV, adaptation was reduced consistent with the presence of lateral inhibitory connections.

It must be concluded from the data of this chapter that tuning-curves do not represent the input bandwidth of a channel, i.e. the range of frequencies activating a channel, because adaptation is restricted to the frequency (F_m and F_c) selective level of FM-specific channels and both adaptation and tuning-curves represent adapting lateral inhibitory connections between these channels. Thus, two stages of F_c-selectivity can be distinguished, the input bandwidth, and the selectivity at the level of FM-specific channels represented by tuning-curves, ie. the bandwidth of adaptation effects. As stated earlier, the activation of a particular FM-specific channel is a function of ±ΔF of the adapting-stimulus within limits defined by a Gaussian filter in the F_c domain. This filter can be regarded as representing the input bandwidth of a channel, the effective bandwidth being given by the PMV, the optimal value of ±ΔF producing maximum activation of the channel. As a consequence of the input bandwidths, channels other than the F_c channel will be stimulated by the sweeps or portions thereof, but only a limited range of channels described by the F_c tuning-curves will adapt or "release" the test channel.

The difference between Gaussian filter bandwidth and tuning-curve bandwidth showsthe selectivity of the system to carrier-frequency to be improved at the FM-specific level. The function of the inhibition might be to reduce activity in channels adjacent to the F_c channel sharpening the response at the channel level. Inhibition might also "clear" channels in preparation for the next FM stimulus.

When test- and adapting-frequencies differ, as in tuning-curve experiments, ±ΔF determines the level of activation of the adapting channel, and therefore its adapting influence upon adjacent channels, as well as the range of F_c-channels activated. It does not determine the bandwidth of adapting connections between channels which is the critical factor determining tuning-curve bandwidth and the independence of tuning-curve bandwidth from ±ΔF (Chapter 4). This independence of tuning-curve bandwidth from ±ΔF is implicit in the convergence of the adaptation versus ±ΔF functions, because if bandwidth was reduced at smaller values of ±ΔF, no convergence would be predicted because the channels would not overlap.

As stated earlier, the functions of adaptation versus ±ΔF show the same characteristics when test- and adapting-frequencies differ as they do when these frequencies are equal. This is also consistent with the inhibition model and the Gaussian filter as input bandwidth. Because the response of the adapting channel is a function of ±ΔF the adaptation it delivers to the test-channel will show the same function with respect to ±ΔF. This would be true even if the test channel was also activated to some smaller extent by the adapting frequency.

In summary, the model now proposed is that the FM system examined so far can be considered as a two-dimensional array of channels defined by their best F_c and F_m and connected by lateral-inhibitory connections.

These connections determine the strength and bandwidth of adaptation (tuning-curves) and presumably the systems selectivity to F_c and F_m. Because channels are tuned to F_c as well as F_m, the activation of a particular channel is a function of ±ΔF. Facilitation effects reflect the bandwidth of inhibitory connections and "release-from-inhibition" which acts to sharpen the systems tuning. Adaptation is an after-effect of prolonged inhibition via the lateral inhibitory connections whose primary role is the production of improved frequency selectivity.

In terms of this model, the decline in adaptation with large values of ±ΔF found in Chapter 3 and attributed to lateral-inhibitory side-bands can represent; (1) lateral-inhibitory side-bands of the input bandwidth which when activated reduce the activity arriving at the F_c channel; (2) activation of "releasing" channels by the sweeps such that adapting activity in channels adjacent to the test-channel is reduced; (3) both these factors. Both factors would predict a flattening out of the decline in adaptation if the sweeps within the Gaussian filter remained constant. Some evidence for this can be seen in the curves of Chapter 3. Unfortunately, data for wider excursions was not collected.

The model is discussed in more detail in Chapter 9, as is a possible basis for F_m tuning.

CHAPTER 6

6.1 Introduction

The experiments reported in this chapter deal with elevations of FM thresholds by various adapting stimuli (Fig. 6.1) at a number of carrier-frequencies.

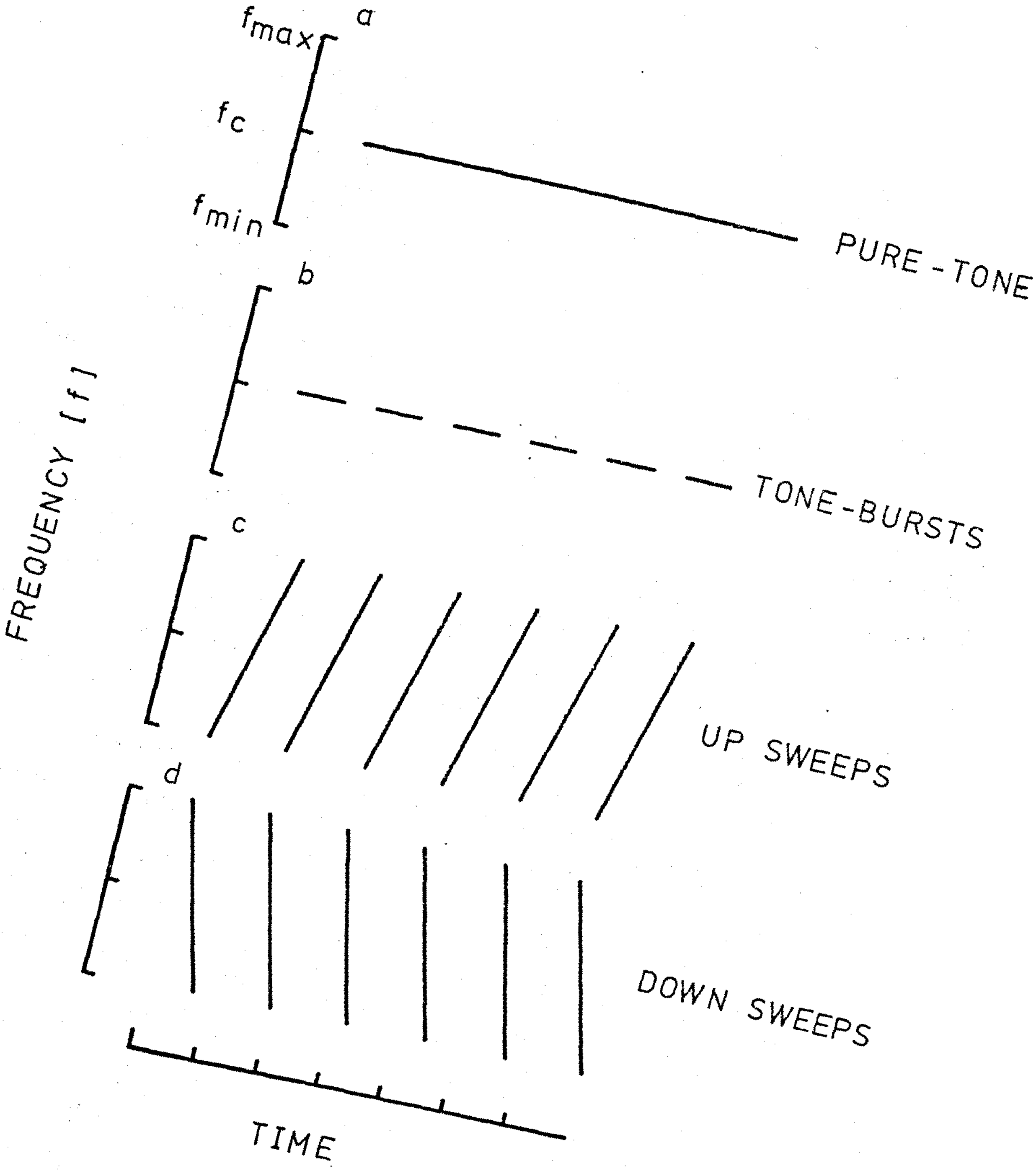
FM adapting stimuli (Fig. 6.1c and d) consisted of upward- or downward-going linear frequency sweeps separated by silent gaps. The experiments were designed, in part, to test the effectiveness of these stimuli which have a number of advantages over the periodic-FM adapting stimuli employed in earlier chapters. Firstly, sweep extent (frequency deviation), duration and rate of change of frequency can be specified and manipulated without altering modulation-frequency or repetition-rate. Obviously, the sweep variables cannot be varied independently and a limit would be set on sweep duration consistent with maintaining a constant repetition rate (see Chapter 3). Secondly, the sweeps are comparable in form, frequency region and duration to some formant transitions of human speech (see Lehiste and Peterson, 1961). Though natural speech rarely contains rapidly repeated, identical transitions the repetitive feature of the linear-sweep adapting-stimuli is similar to the stimulus regime of speech adaptation experiments with adapting stimuli consisting of rapidly repeated syllables (e.g. Bailey, 1973). If FM-channels are assumed to be involved in speech perception, it is useful to know they respond to speech-like frequency transitions. Thirdly, the sweeps occur in one direction of frequency change only allowing the directional specificity of adaptation effects to be studied with the appropriate test-stimuli.

The tone-burst stimuli (Fig. 3.1b) have the same characteristic as the FM-stimuli except for the frequency-sweeps. They act as a control stimulus for the feature-specificity of adaptation effects.

Fig. 6.1. Frequency-time plots of the adaptation interval stimuli.

(a) Pure-tone stimulus (unadapted threshold).
(b) Tone-bursts.
(c) Upward-going frequency sweeps.
(d) Downward-going frequency sweeps.

The duration of bursts on sweeps was 75ms and the repetition rate of stimuli (b)-(d) was 8 per second.


f_{max}
f_c
f_{min}
a
PURE-TONE
b
TONE-BURSTS
c
UP SWEEPS
d
DOWN SWEEPS
FREQUENCY [f]
TIME

6.2 Experiments with linear sweeps: Sinusoidal-FM test-stimuli

6.2.1 Methods

Test-stimuli were of 500 ms duration. The duration of the silent gaps was 100 ms (see Fig. 2.1). The FM test-stimulus consisted of sinusoidal FM with a modulation-frequency of 8 Hz. Three adapting-stimuli were used:

(a) unmodulated tone-bursts of 75 ms duration separated by 50 ms gaps, i.e. a cycle-time of 125 ms (Fig. 3b),

(b) tone-bursts with upward-going linear frequency sweeps. Sweep (burst) duration was 75 ms, gaps 50 ms, i.e. a cycle time of 125 ms (Fig. 3c),

(c) *as in (b) but with downward-going frequency sweeps* (Fig. 3d).

Unadapted thresholds were determined with a pure-tone within the adaptation interval (Fig. 3a).

The adapting-stimuli had repetition-rates of 8 per second equal to that of the FM test stimulus. The value of centre-frequency (F_c) of the adapting-stimuli was also equal to that of the test-stimulus. This assumed that for a particular value of F_c the test- and adapting-stimuli were processed by the same "channel" tuned to an 8 Hz modulation-frequency and the value of F_c.

The experiment was carried out at all four values of F_c, i.e. 0.25, 0.5, 1.0 and 4.5 kHz. The values of the *frequency excursion and rate-of-change of frequency of the FM adapting-stimuli* are shown in Table 3.1.

The values of ±ΔF were arbitarily chosen, the only qualification being that they produced large elevations of test thresholds. At 0.5 kHz the value of ±31 Hz for RBG only produced small elevations so the value was doubled *before the experiment* with VJG. *This new value was used for* RBG in later experiments. Except for 4.5 kHz most of the values chosen were at or near the PMV for the values of F_c used (see Chapter 3).

6.2.2 Results and discussion

Adaptation factors at the various values of F_c used are shown in Fig. 6.2. Adaptation to up-, down-sweeps and tone-bursts are shown. Data points are the means of three threshold estimates. Vertical bars are standard deviations. The linear sweep adapting sweeps thus constitute effective stimuli for FM-adaptation. Though these stimuli were used in Chapter 3 and 4 these experiments were carried out at a later date to those reported here. Linear sweeps are therefore an important stimulus for the reasons discussed in the introduction to this chapter. The 0.5 kHz sweeps for RBG produced smaller elevations of threshold.

Of some interest is the finding that tone-burst stimuli adapt sinusoidal-FM thresholds. The data indicates a trend of increasing adaptation with increasing frequency, especially in the data of RBG. No effect was present at 0.25 kHz. This effect of tone-bursts is inconsistent with the feature-specificity of FM adaptation reported by Kay and Matthews (1972). One would not expect an FM-channel to respond to, and be adapted by, tone-bursts. The effect is investigated further, later in this chapter.

6.3 Experiments with linear sweeps: Single linear sweep test-stimuli

Test-stimuli consisted of single linear frequency sweeps allowing the possibility of direction-specific coding of FM to be examined with the linear sweep adapting-stimuli discussed above.

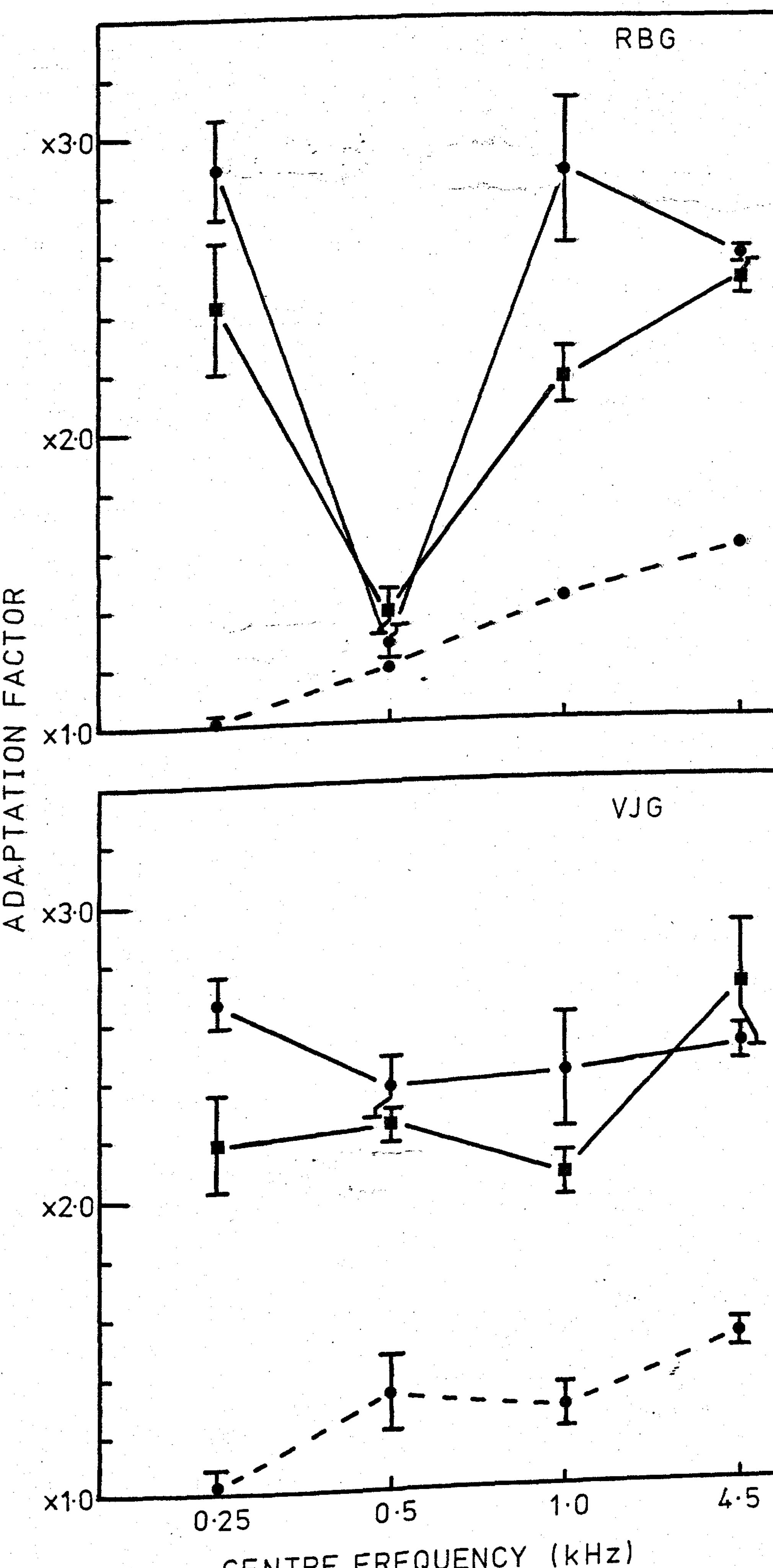
6.3.1 Methods

Test-stimuli were of 62.5 ms duration. Gaps 1 and 2 were of 319 ms duration, gap 2 was of 537 ms duration (see lower diagram of Fig. 2.1). These values ensured the interval between adapting-stimuli was the same as in the previous experiment and that any decay of adaptation during this interval would be comparable. The FM test-stimuli were upward- and downward-going single linear frequency sweeps. The adapting-stimuli were identical

Fig. 6.2. Adaptation factors as a function of F_c with adapting-stimulus type as the parameter. The test stimulus was sinusoidal FM. The key is as follows:

●- - -●	tone-bursts
●——●	up-sweeps
■——■	down-sweeps

(a) RBG (b) VJG


RBG
VJG
ADAPTATION FACTOR
x3·0
x2·0
x1·0
x3·0
x2·0
x1·0
0·25
0·5
1·0
4·5
CENTRE FREQUENCY (kHz)

to those used in the previous experiment except that the value of ±ΔF at 0.5 kHz was increased to ±62.5 Hz for RBG. The experiment was carried out at 0.5, 1.0 and 4.5 kHz. The value of F_c of the test- and adapting-stimuli was equal. Unadapted thresholds were determined, as usual, with a pure-tone in the adaptation interval. Both Ss participated in the experiment.

6.3.2 Results and discussion

Adaptation factors to up-sweeps, down-sweeps and tone-bursts at the three values of F_c are shown in Fig. 6.3. The left-hand graphs are the up-sweep test data, those on the right the down-sweep data. Data points are the means of three threshold estimates and vertical bars represent ±1 standard deviation. Unadapted thresholds are reported and discussed in Chapter 8. The data indicate that only the FM adapting-stimuli with the same direction of sweep as the test-stimulus produce threshold elevations. For example, in the top left-hand graph of Fig. 6.3 (RBG/up-sweep test) both tone-burst and down-sweep adapting stimuli were ineffective, up-sweeps were. Thus support is provided for the existence of direction-specific adaptation effects. This is discussed in more detail in the discussion at the end of this chapter.

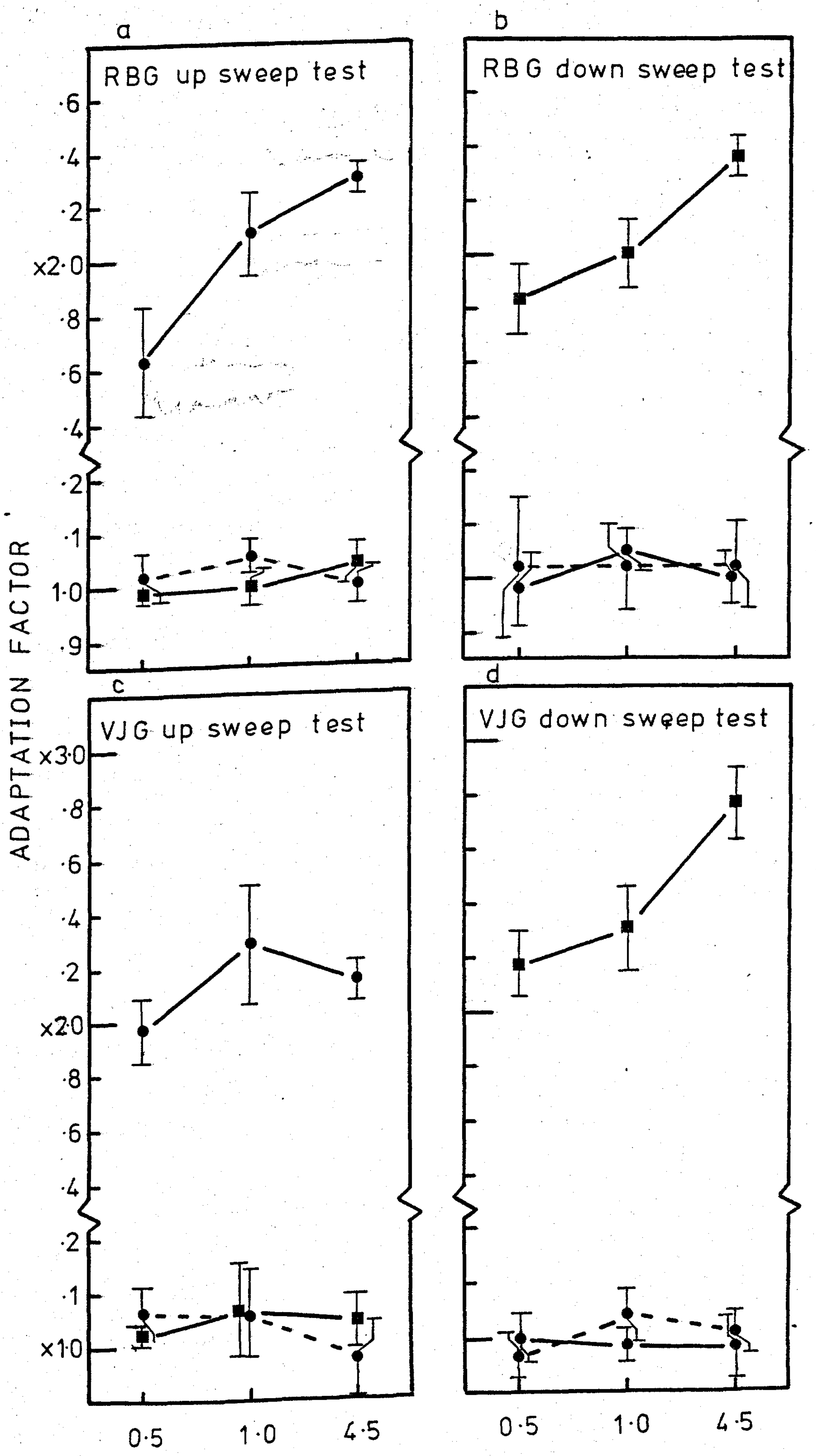
The fact the effect of tone-bursts on FM-thresholds disappears with single sweep test-stimuli at all frequencies suggest the test-stimulus must be repetitive for the effect to occur. Before discussing the effect in more detail two more experiments are reported.

6.4 Examination of the effect of tone-bursts on sinusoidal-FM thresholds

This experiment was designed to ensure the effect of tone-bursts was not an artifact related, for instance, to a single duration of bursts, and to examine the robustness of the effect.

Fig. 6.3. Adaptation factors as a function of F_c with adapting-stimulus type as the parameter. Test stimuli were single linear frequency sweeps. Key as in Fig. 6.2.

(a) RBG, up-sweep test.
(b) RBG, down-sweep test.
(c) VJG, up-sweep test.
(d) VJG, down-sweep test.


a
RBG up sweep test
b
RBG down sweep test
c
VJG up sweep test
d
VJG down sweep test
ADAPTATION FACTOR
·6
·4
·2
x2·0
·8
·6
·4
·2
·1
1·0
·9
x3·0
·8
·6
·4
·2
x2·0
·8
·6
·4
·2
·1
x1·0
0·5
1·0
4·5
0·5
1·0
4·5

6.4.1 Methods

The test-stimuli (sinusoidal-FM) and 2IFC procedure were identical to those of the experiment reported in Section 6.2.1. Adapting-stimuli were tone-bursts of 5, 10, 25, 50, 100 ms duration. Data for 75 ms tone-bursts were taken from the previous experiment (Section 6.2). The tone-burst repetition-rate was 8 per second equal to the test-stimulus modulation-frequency. The experiment was carried out at 0.5, 1.0 and 4.5 kHz, i.e. the frequencies at which the effect was found in Section 6.2. Single threshold estimates at 0.25 kHz confirmed that no effect was present at this frequency consistent with the lack of effect at 75 ms (Fig. 6.2). It was concluded that any effect at 0.25 kHz was too weak to warrant further investigation. Only RBG participated in the experiment.

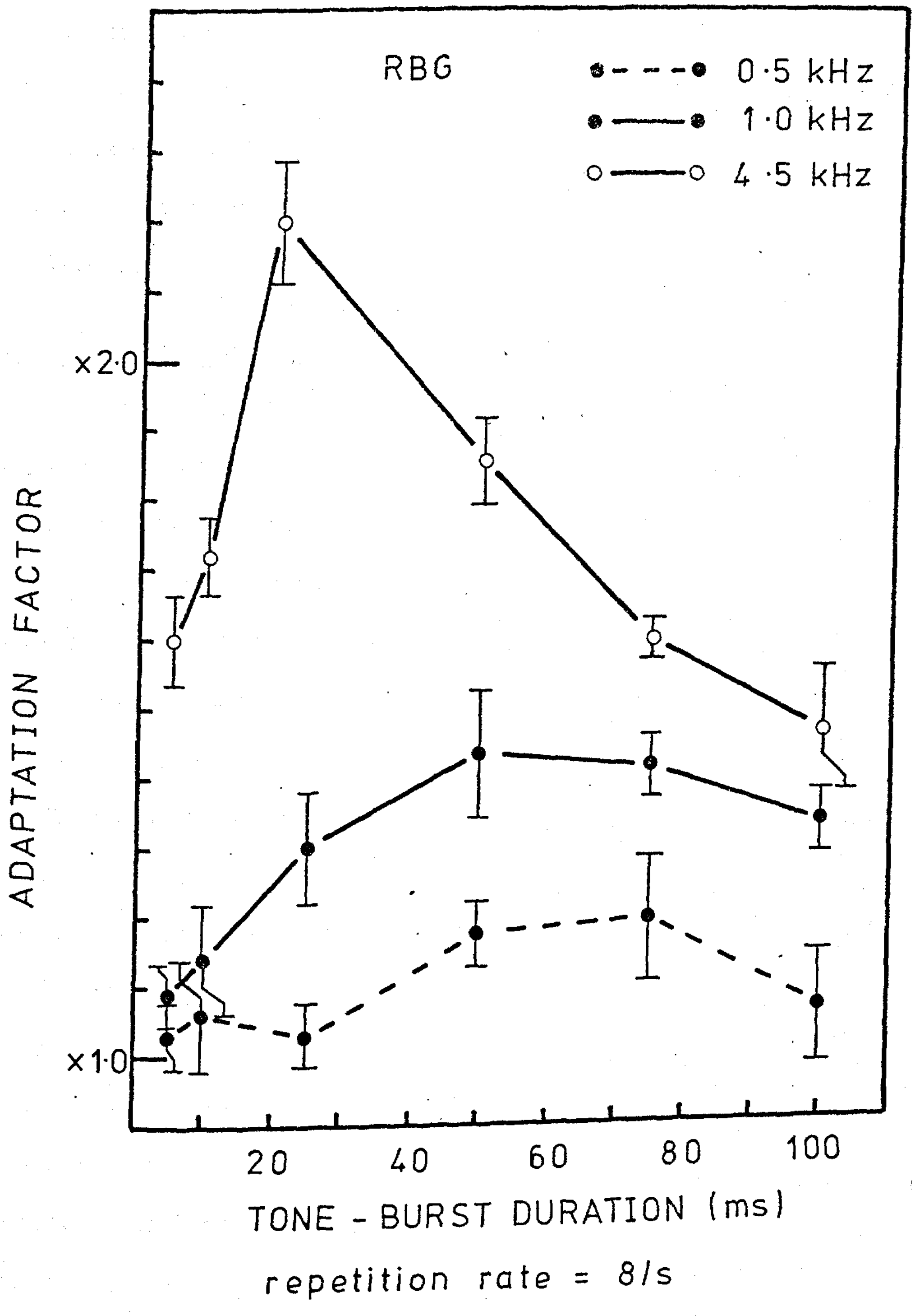
6.4.2 Results and discussion

Adaptation factors as a function of tone-burst duration with F_c as the parameter are shown in Fig. 6.4. Data points are the means of three threshold estimates, vertical bars represent ±1 standard deviations. All burst-durations except the lowest and highest values at 0.5 kHz produce elevations of sinusoidal-FM thresholds. The effect increases with increasing F_c over the range of burst-durations examined. The elevations at 4.5 kHz are of the order of those produced by some FM-stimuli. The data show a preferred duration of burst, especially at 4.5 kHz. The preferred duration at 4.5 kHz is 25 ms, at 0.5 and 1.0 kHz the preferred range of duration is between 40 and 60 ms. For the moment it is enough to note that the effect is reproducible over a range of burst parameters.

6.5 Effect of tone-bursts: Triangular-FM test-stimuli

It was found that the effect of tone-bursts disappeared when single linear sweep test-stimuli were used. One possibility for this is that the effect only occurs with repetitive test-stimuli. To test this triangular-

Fig. 6.4. Plots of adaptation factor as a function of tone-burst duration for tone-burst adapting-stimuli. F_c is the parameter. The key is on the figure.


RBG
0·5 kHz
1·0 kHz
4·5 kHz
ADAPTATION FACTOR
x2·0
x1·0
20
40
60
80
100
TONE - BURST DURATION (ms)
repetition rate = 8/s

FM test-stimuli were employed where the number of cycles of the modulating-waveform, i.e. the number of repetitions, was varied.

6.5.1 Methods

The experiment was carried out at 1 kHz for RBG only. Adapting-stimuli were identical to those used in Section 6.2 at 1 kHz. The modulation-frequency of the test stimulus was 8 Hz. The experimental variable was the number of cycles of the test-stimulus modulating-waveform. Number of cycles were 1, 2, 3, 4, 6 and 8. Unadapted and adapted thresholds were measured in each experimental condition. Table 6.2 summarises the test conditions.

6.5.2 Results and discussion

Adaptation factors are shown in Fig. 6.5. Data points are the means of three threshold estimates. Vertical bars represent ±1 standard deviation. It can be seen that both up- and down-sweeps elevate the test thresholds at all the numbers of cycles used, and that the effect of sweeps is always greater than the effects of tone-bursts.

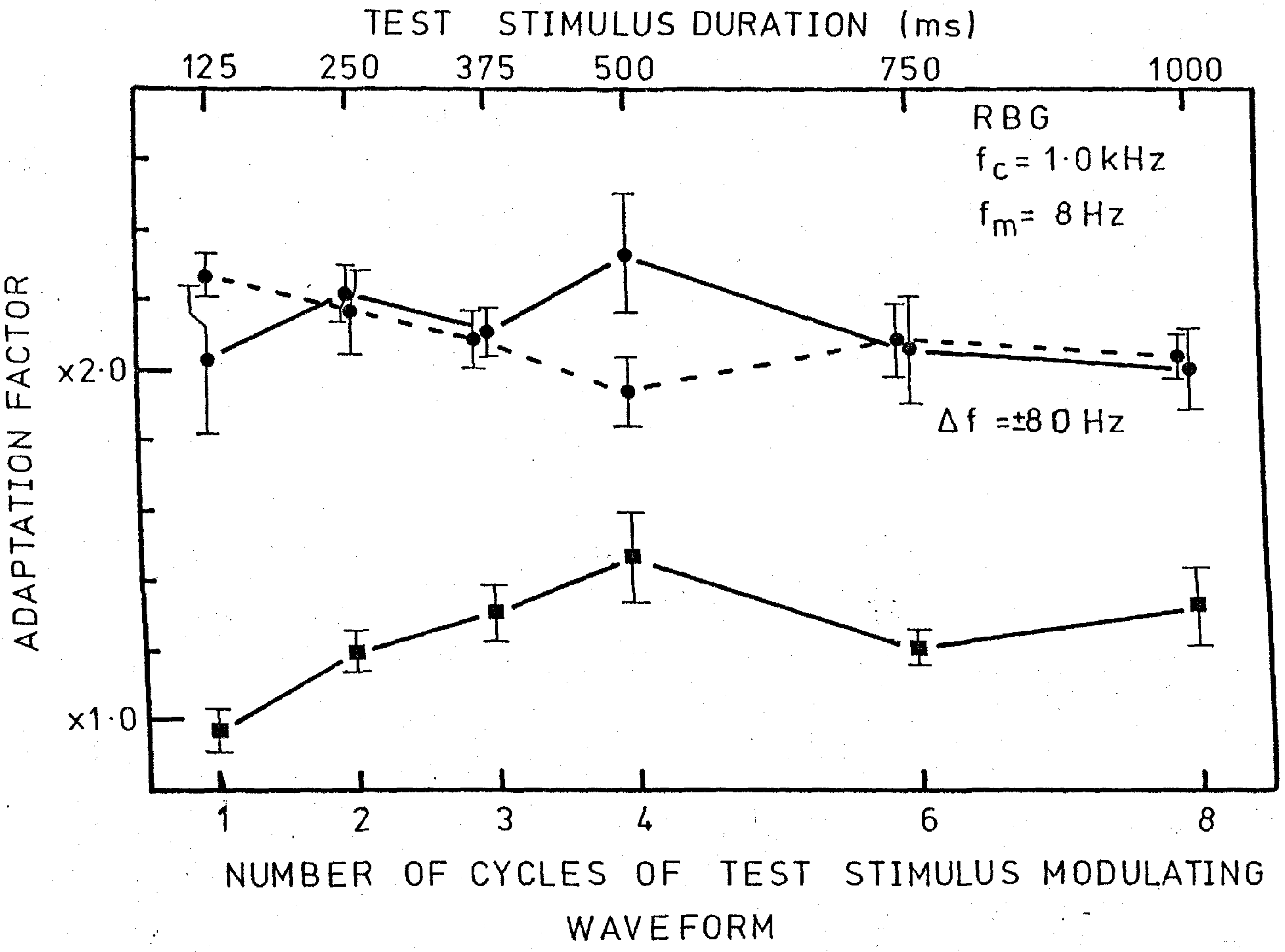
The adaptation produced by sweeps is roughly equal in each test condition and except for the 4-cycle test-stimulus no differences in adaptation to up- and down-sweeps occurs. The present experiment at 4-cycles is identical to the experiment reported in Section 6.2, except for the difference in test-stimulus modulating-waveform. That the adaptation to both up- and down-sweeps is markedly lower than in the Section 6.2 experiment suggests the relationship between test- and adapting-sweep variables is of some importance in determining adaptation. This relationship cannot be of critical importance however, because in most studies of FM-adaptation, including this one, the test- and adapting-stimuli have very different temporal characteristics.

Fig. 6.5. Adaptation factor as a function of the number of cycles of a triangular-FM test-stimulus modulating-waveform. Adapting stimulus type is the parameter. The key is as follows:

tone-bursts

up-sweeps

down-sweeps


TEST STIMULUS DURATION (ms)
125
250
375
500
750
1000
RBG
f_c = 1·0 kHz
f_m = 8 Hz
Δf =±8 0 Hz
ADAPTATION FACTOR
x2·0
x1·0
1
2
3
4
6
8
NUMBER OF CYCLES OF TEST STIMULUS MODULATING WAVEFORM

The experiment confirms the role of test-stimulus repetition in determining the effects of tone-bursts. This effect increases as the number of cycles of the test-stimulus increases. A number of hypotheses concerning the basis of this effect are discussed in the next section.

6.6 Summary and general discussion

The two main findings of this chapter are:

(1) the existence of directionally-specific effects in FM-adaptation, and

(2) that the effect of tone-bursts without an FM component are related to the repetitive character of FM test-stimuli.

These two findings are discussed separately below.

(1) Directional-Specificity

The directionally-specific data suggests the FM processing system is divided into two functionally separate channels, one coding upward-going frequency transitions, the other downward-going transitions. This specificity is in accord with neurophysiological evidence for units showing a specific or preferential response to a particular direction of frequency transition (e.g. Whitfield and Evans, 1965; see Chapter 1, Section 1.3). The data of Chapter 5 suggested adaptation was an after-effect of inhibition between channels tuned to both F_c and F_m. The tuning (frequency-selectivity) of adaptation effects was also a consequence of the range and strength of lateral inhibitory connections. Implicit in this model is the assumption that a channel's output to a test stimulus determines threshold and that this output is reduced by adaptation. It follows that detection of FM occurs after the processing of FM stimuli by frequency-selective channels. If it occurred before this stage of processing adaptation would not occur.

The additional factor of directional-specificity must now be incorporated into this model. Directional-specificity must be established before the frequency-selective stage of processing, i.e. the level at which adaptation occurs. If directional-specificity was established above this stage of processing, no directional-specific adaptation would be found. It must be assumed that two separate directional-specific channels exist each with a frequency-selective stage of processing which is the locus of the adaptation mechanism.

Sinusoidal-FM can now be regarded as consisting of two functionally separate, non-interacting (from the point of view of adaptation) FM components, upward-going transitions and downward-going transitions. Thus, in the experiment of Section 6.2 both directions of FM adapting sweep adapt sinusoidal-FM thresholds. It must be assumed the effect of up-sweeps is a result of adaptation of the up-specific channel only and, similarly, down-sweep adapting stimuli only affect the down-sweep component of the sinusoidal-FM test. It must also be assumed that the detection of sinusoidal-FM (and triangular-FM) is based on the activity in both direction-specific channels because both directions of adapting frequency sweeps elevate thresholds.

More recent experiments (Tansley and Regan, 1980) have confirmed the existence of directional-specific FM and AM adaptation effects (see Chapter 1). A psychophysical, "black-box" model of the various stages of processing of FM stimuli is presented in Fig. 6.6.

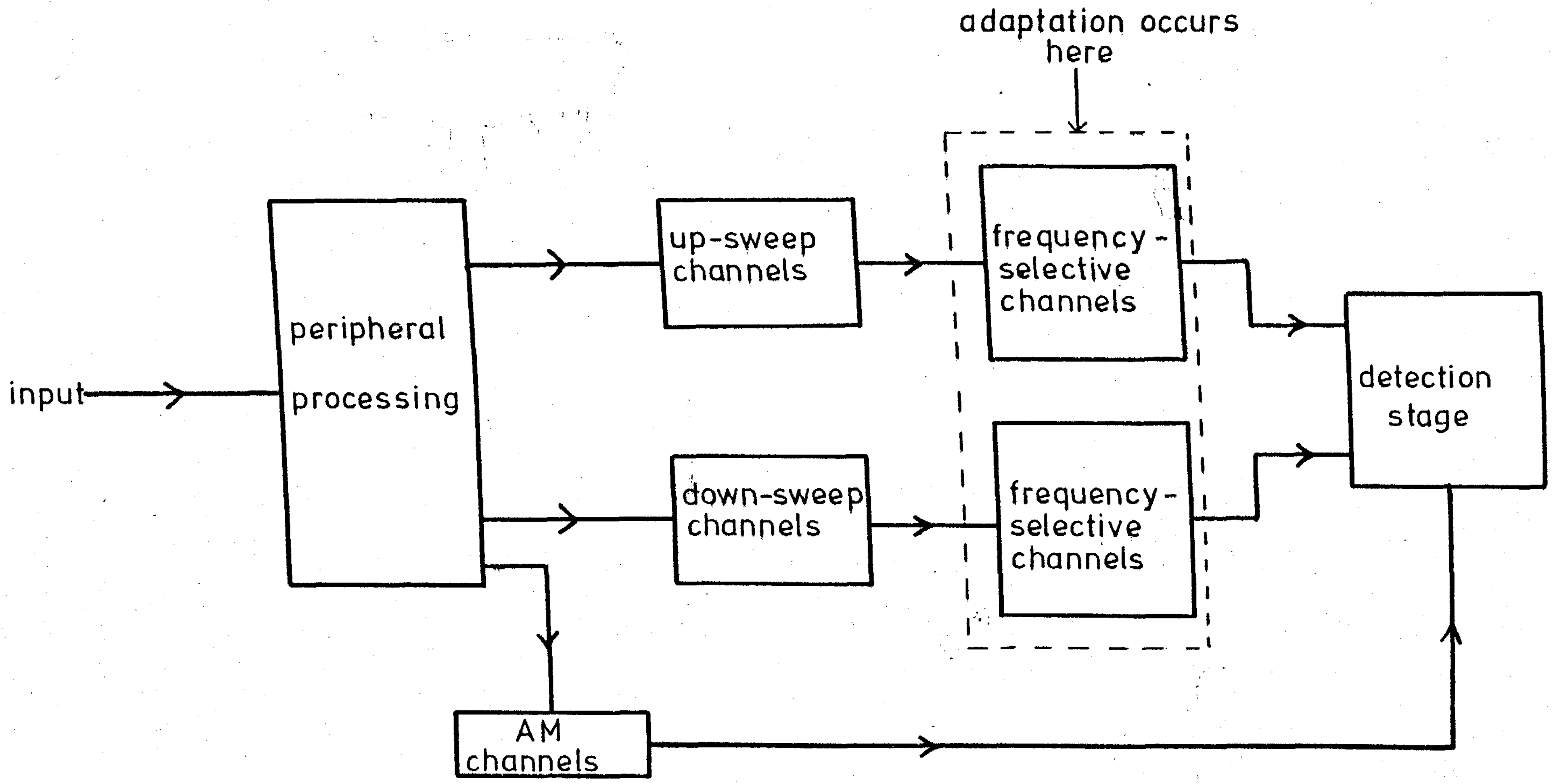
(2) The Effect of Tone-Bursts

This effect is important because it violates the feature-specificity of FM adaptation. As mentioned in the introduction, other workers have found effects of FM on AM or vice versa (Kay and Matthews, 1972; Regan and Tansley, 1979; Tansley and Regan, 1980). Two separate hypotheses for the effect are discussed below.

(a) Repetition hypothesis

The finding that the effect of tone-burst requires a repetitive

Fig. 6.6. A model of the processing of FM stimuli.


adaptation occurs here
input
peripheral processing
up-sweep channels
down-sweep channels
AM channels
frequency-selective channels
frequency-selective channels
detection stage

test-stimulus may be regarded as evidence for an effect based on repetition per se and therefore a channel carrying repetition information. Repetition refers to any periodic (in this study) time-varying attribute of a stimulus. Whether periodic repetition is a necessary condition for the effect requires experimental confirmation.

This interpretation of the data requires that the subject utilises repetition information in the detection of periodic-FM independently of FM information. Thus both FM and repetition information distinguish between the unmodulated and modulated test stimuli in experiments involving sinusoidal-FM. Adaptation of the repetition channel with an appropriate stimulus would degrade the repetition information and the resultant loss of detectability of the test would require compensation in the form of an increased test threshold (expressed as $\pm\Delta F$). Obviously the effect would not occur with single sweep test-stimuli which are not repetitive.

Because all the FM adapting-stimuli used in the study are repetitive adaptation of periodic-FM test-stimuli by these stimuli must be regarded as involving two components, a repetition component and an FM effect proper. This presents the greatest difficulty for the repetition hypothesis because unless the repetition channels display almost exactly the same F_m and F_c tuning properties as do FM channels (see Chapters 3-5) it would be impossible to explain facilitation effects and indeed any adaptation lower than a base-line adaptation set by the repetition component of the adapting-stimuli.

(b) AM hypothesis

There is evidence from a number of sources that FM and AM are processed separately by the auditory system (Feth, 1972; Kay and Matthews, 1972; Zagorski, 1975; Coninx, 1978a,b; Regan and Tansley, 1979; Tansley and Regan, 1980) [see Chapter 1]. It is possible that the dependence of loudness upon frequency, as defined by the equal loudness contour (ELC) may provide the explanation of the effect of tone-bursts. Loudness fluctuations associated with test-stimulus FM may be coded by AM channels and contribute to the detection of the test modulation. Tone-bursts, an AM stimulus, would adapt the AM channels carrying this information. The fact that the effect of tone-bursts disappeared with single-sweep and single-cycle triangular-FM could be explained by assuming the associated loudness fluctuations in these test-stimuli were too small to aid detection. Over a number of repetitions of a test-waveform, the fluctuations may become detectable and useful in the task of differentiating between the unmodulated and modulated test stimuli. If there is, for instance, a significant slope to the ELC around the F_c of the test stimulus which produces loudness fluctuations, then the adapting stimulus would also have a corresponding AM component. It might be assumed that two adaptation components exist, FM and AM, in adaptation with FM-stimuli. Loudness-fluctuations associated with other frequency regions of sweeps might be conveniently ignored if AM channels are assumed to be tuned to F_c. Unlike the repetition component hypothesised above, an AM component of FM adapting-stimuli could be of little consequence, especially if one considers that the adaptation produced by the tone-bursts (essentially a 100% square-wave modulated AM stimulus) was usually quite small. The size of the effect must reflect the importance of the test AM component in detection as well as the effectiveness of the AM adapting component. Against the AM hypothesis is the finding that the effect of tone-bursts is "tuned" to burst duration. Changing the burst duration while holding repetition rate constant (Section 6.4) does not alter the characteristics of the amplitude transitions nor the total number of transitions occurring in the adaptation interval. The AM variables that might be expected to influence adaptation of the test AM component are unchanged.

It is clear that the role of the ELC in FM adaptation needs to be examined to test the two hypotheses presented above. As a final point

Coninx (1978a) found the slopes of the ELC to be steeper at higher frequencies such that greater loudness fluctuations associated with FM were introduced. This is consistent with the finding that the effect of tone-bursts increases with increasing frequency (Fig. 6.4) and supports the AM hypothesis. Further support of the AM hypothesis comes from the experiment of Section 6.5 where adaptation was measured as a function of the number of cycles of the test-stimulus modulating-waveform. As predicted by the repetition hypothesis the tone-burst effect increased with the number of repetitions of the test. The adaptation to sweeps remained constant however when it would be expected to follow the rise in the tone-burst effect as the effectiveness of the sweep repetition component increased.

Directional specificity is examined further in the next two chapters.

TABLE 6.1

The values of the frequency-deviation ±ΔF (Hz) and rate of change of frequency (df/dt) of the FM adapting stimuli for all values of carrier-frequency (F_c) used.

F_c (kHz)	±ΔF (Hz)	df/dt (Hz/s)
0.25	±50	1333
0.5	±31 ±62.5 for VJG	833.3 1667
1.0	±80	2134
4.5	±187.5	5000

TABLE 6.2

Summary of test conditions. The time between adaptation intervals in the 1 to 4 cycles conditions was 1.3s (as in earlier experiments). For the 6 and 8 cycles conditions this time were 1.8s and 2.3s respectively.

Number of cycles	Test stimulus duration (ms)	Duration of gaps 1 & 3 (ms)	Duration of gap 2 (ms)
1	125	287.5	475
2	250	225	350
3	375	162.5	225
4	500	100	100
6	750	100	100
8	1000	100	100

CHAPTER 7

7.1 Introduction

Directional-specific effects are examined with a number of different test- and adapting-stimuli.

7.2 Repetitive linear sweep test-stimuli

7.2.1 Methods

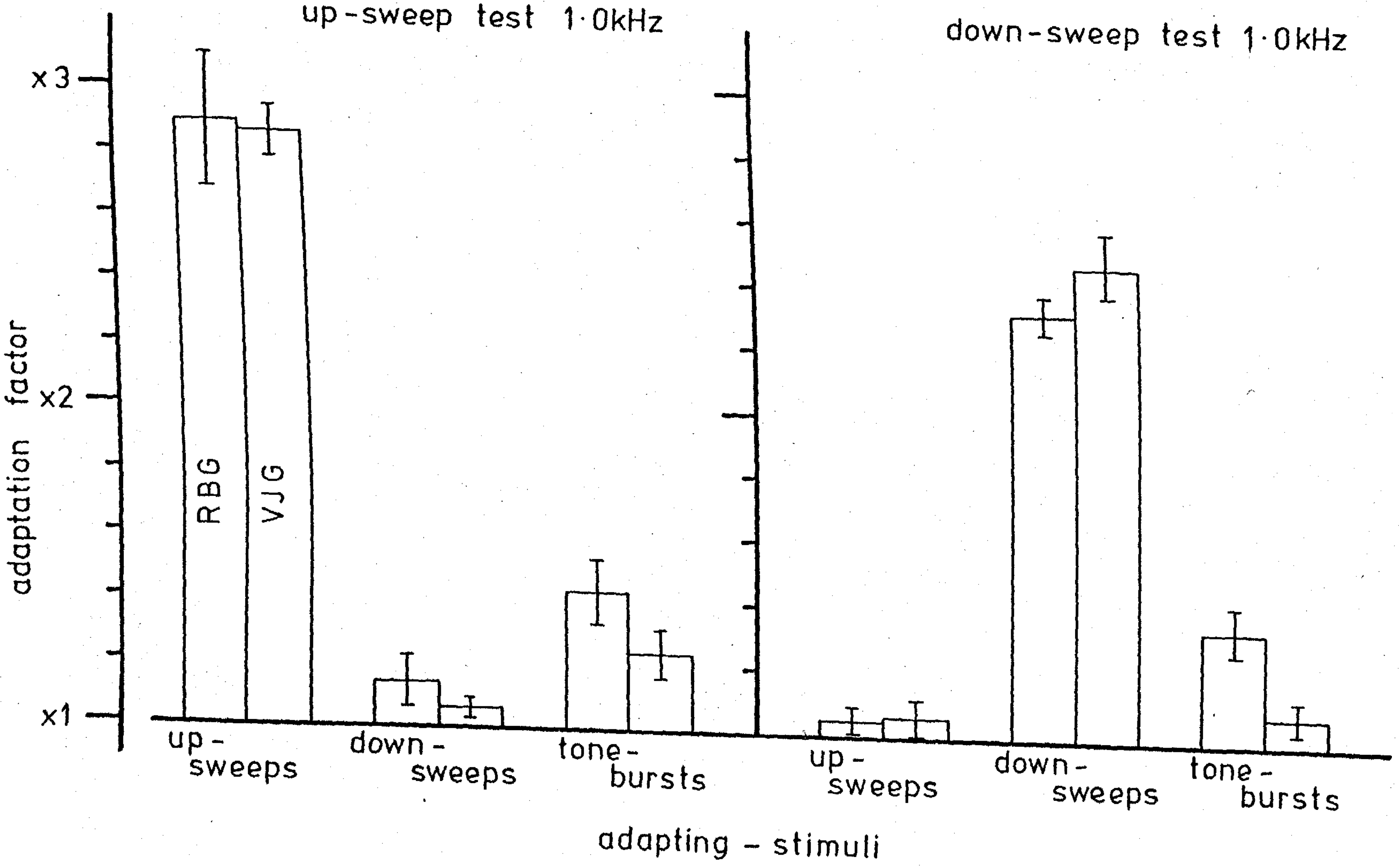
Test-stimuli were either upward- or downward-going linear frequency sweeps. Sweeps were of 62.5 ms duration, separated by silent gaps of the same duration. The repetition rate was thus 8 per second. Four sweeps occurred in the 500 ms test interval. Adapting-stimuli were tone-bursts, up-sweeps and down-sweeps (Fig. 6.1) of 62.5 ms duration and having the same repetition rate as the test-stimulus. The frequency-deviation of the FM adapting sweeps was ±80 Hz. The experiment was carried out at F_c = 1.0 kHz for both Ss. The unmodulated test-stimulus consisted of tone-bursts of 62.5 ms duration and a repetition rate of 8 per second. The subject's task is to decide which tone-burst stimulus contains frequency sweeps.

7.2.2 Results and discussion

Figure 7.1 shows histograms of mean adaptation factor (3 threshold stimulus) for each adapting-stimulus. The left-hand figure shows the data for the up-sweep test, the right-hand the data for the down-sweep test. For each pair of histograms at a particular adapting-stimulus, the left-hand histogram is the data for RBG and the right the data for VJG. This is true of every histogram presented in this chapter. The vertical bars are ±1 standard deviation.

The main finding of the experiment confirms the existence of directional-specific adaptation, i.e. only the adapting-stimulus with the same direction of frequency sweep as the test is an effective adapting-stimulus. The effects of tone-bursts reappears apparently confirming the

Fig. 7.1. Histograms of mean adaptation factor for various adapting-stimulus conditions. Test stimuli were upward- or downward-going repetitive linear frequency-sweeps with a repetition-rate of 8 per second equal to that of the adapting-stimuli. The left-hand histogram of each pair is the data for RBG, the right the data for VJG. This is true for every figure in this chapter. F_c = 1.0 kHz. Vertical bars are ±1 standard deviation.


up-sweep test 1·0kHz
down-sweep test 1·0kHz
adaptation factor
x3
x2
x1
RBG
VJG
up-sweeps
down-sweeps
tone-bursts
up-sweeps
down-sweeps
tone-bursts
adapting - stimuli

repetition hypothesis in that the effect was not present with single linear sweeps but is with repetitive linear sweeps. However, because the unmodulated test interval is also repetitive, repetition information would not aid the task of detecting the FM test-stimulus. The experiment with repetitive linear sweeps must be done in this way because tone-bursts with or without FM would be instantly distinguished from an unmodulated, continuous comparison. The experiment provides evidence against the repetition hypothesis. Even if repetition information was assumed to have a role, the repetition hypothesis could not explain the fact that FM-sweeps in the opposite direction do not adapt thresholds when they would be assumed to have a repetition component as effective as the tone-burst adapting-stimulus.

Recently, Tansley and Regan (1980) have confirmed the existence of directional-specific FM adaptation effects using similar test-stimuli. These were 500 ms ramps spaced apart by 200 ms gaps where one test-interval contained 7 ramps.

7.3 Sawtooth-modulated test stimuli

Sawtooth-FM might be expected to be a suitable stimulus for demonstrating directional-specific adaptation effects. Rutland (1976) found sawtooth-AM stimuli produced AM illusions consistent with the existence of directional-specific AM channels as found by Tansley and Regan (1980).

Upward- and downward-going sawtooth-FM test stimuli were used in conjunction with upward- and downward-going FM sweep adapting-stimuli (Fig. 6.1). The direction of sawtooth-FM refers here to the sweep portion of the waveform.

7.3.1 Methods

The modulation-frequency of the sawtooth-FM test stimulus was 8 Hz. Adapting-stimuli were FM-sweeps (duration = 62.5 ms; repetition-rate = 8 per second). Experiments were carried out at 0.5 kHz for RBG and 0.5 and

1.0 kHz for VJG. The adapting frequency-deviation was ±62.5 Hz at 0.5 kHz and ±80 Hz at 1.0 kHz.

7.3.2 Results and discussion

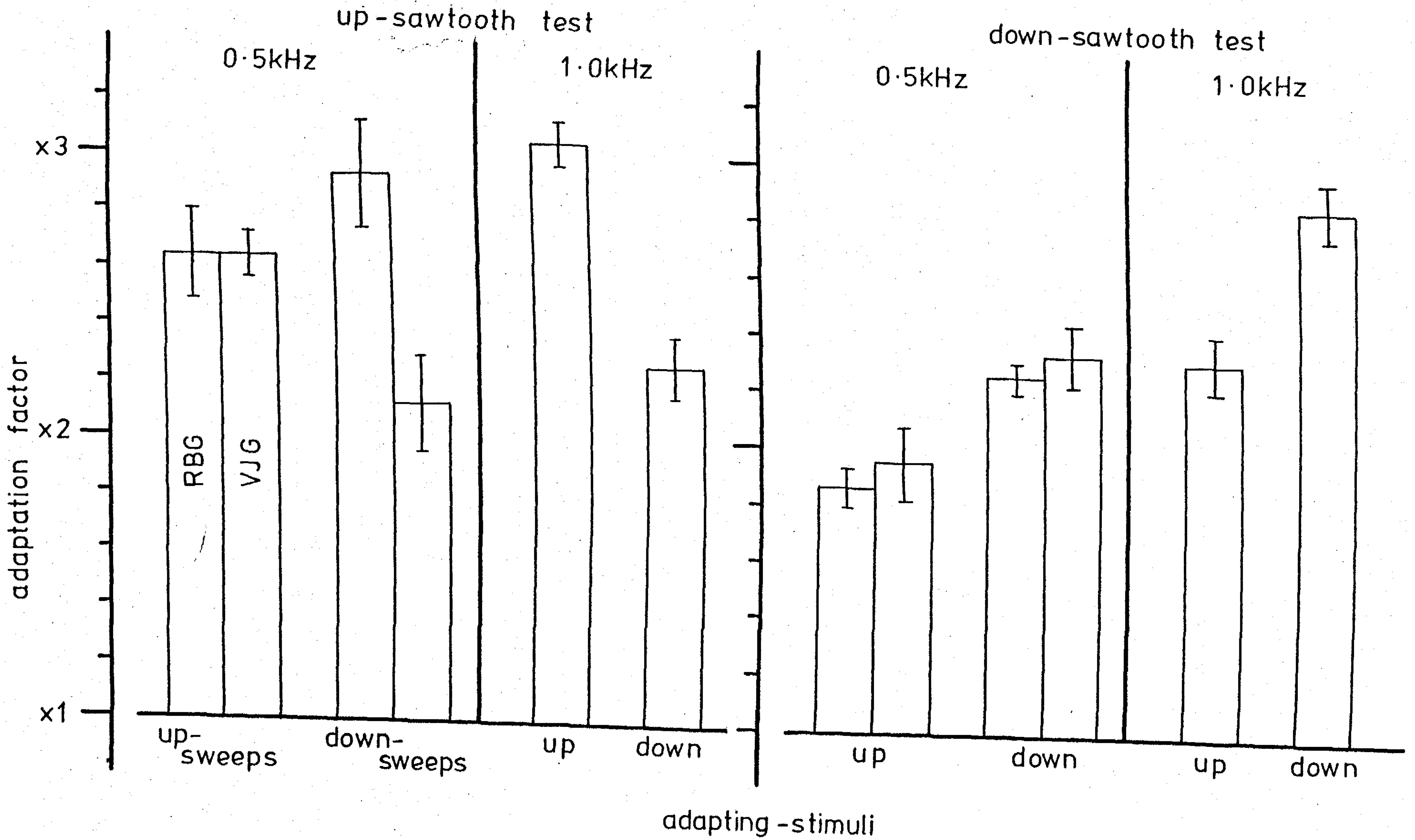
Histograms of mean adaptation factor for the adapting-stimulus conditions are shown in Fig. 7.2. The left-hand graph shows data for the up-sawtooth test condition, the right-hand graph the data for the down-sawtooth condition. Both the 0.5 and 1.0 kHz data are presented in the figure. Three threshold estimates were made in each condition and means and standard deviations calculated.

No directional-specific effects are found with sawtooth-FM test stimuli as both up- and down-sweep adapting-stimuli elevate thresholds in each test-stimulus condition. This suggests sawtooth-FM is not a suitable stimulus for research into directional-specific FM adaptation. It is possible, however, that the effects of FM-sweeps upon sawtooth-FM with sweeps in the opposite direction is due to some other component, AM or repetition features, of the test- and adapting-stimuli. Though this would mean that FM-adaptation was small or non-existent in some stimulus conditions the possibility was tested with single linear frequency-sweep test stimuli and sawtooth-FM adapting-stimuli.

7.4 Single sweep test-stimuli: sawtooth-FM adapting-stimuli

If the lack of directional-specificity found in the previous section were due to an AM (or repetition) component of the test- and adapting-stimuli, then this influence would be removed by using single sweep test-stimuli (see Chapter 6) revealing "pure-FM" adaptation. Sawtooth-FM was used as the adapting-stimulus. If it is an adequate stimulus for directional-specific adaptation, then up-sawtooth would be expected to elevate up-sweep test thresholds only. Similarly, down-sawtooth would only elevate down-sweep thresholds.

Fig. 7.2. Histograms of mean adaptation factor for various adapting-stimulus conditions. Test-stimuli were upward- or downward-going sawtooth FM, where direction refers to the sweep component of waveform. Test modulation-frequency was 8 Hz, adapting repetition-rate 8 per second. F_c = 0.5 kHz (RBG and VJG) or 1.0 kHz (VJG). Vertical bars are ±1 standard deviation.


up-sawtooth test
0·5kHz
1·0kHz
down-sawtooth test
0·5kHz
1·0kHz
adaptation factor
x3
x2
x1
RBG
VJG
up-
sweeps
down-
sweeps
up
down
up
down
up
down
adapting-stimuli

7.4.1 Methods

Test-stimuli were 62.5 ms single linear frequency-sweeps as used in Chapter 6. Adapting-stimuli were up- or down-sawtooth-FM where ±ΔF was ±62.5 Hz at 0.5 kHz and ±80 Hz at 1.0 kHz. The modulation-frequency of the sawtooth-FM was 8 Hz. Both Ss participated in the experiments at 0.5 kHz, only VJG at 1.0 kHz.

7.4.2 Results and discussion

Histograms of the adaptation factor for each adapting condition are shown in Fig. 7.3. The left-hand figure shows the data for the up-sweep test condition, the right-hand the data for the down-sweep test condition. Three threshold estimates were made in each experimental condition and the means and standard deviations calculated.

Once again no directional-specific effects were found. On the basis of earlier experiments with single sweep test-stimuli, no contamination of adaptation by other stimulus components could have occurred. The data suggest that not only the sweeps of sawtooth-FM, but also the extremely rapid transitions between sweeps, are effective FM adapting-stimuli. For example, because down-sweeps do not elevate up-sweep thresholds (Sections 6.3 and 7.2) the effect of the down-sawtooth adapting-stimulus upon single up-sweep thresholds must be due to the rapid upward transitions of this particular stimulus. To test this possibility, square-wave-FM adapting-stimuli were used in conjunction with the test-stimuli of this section.

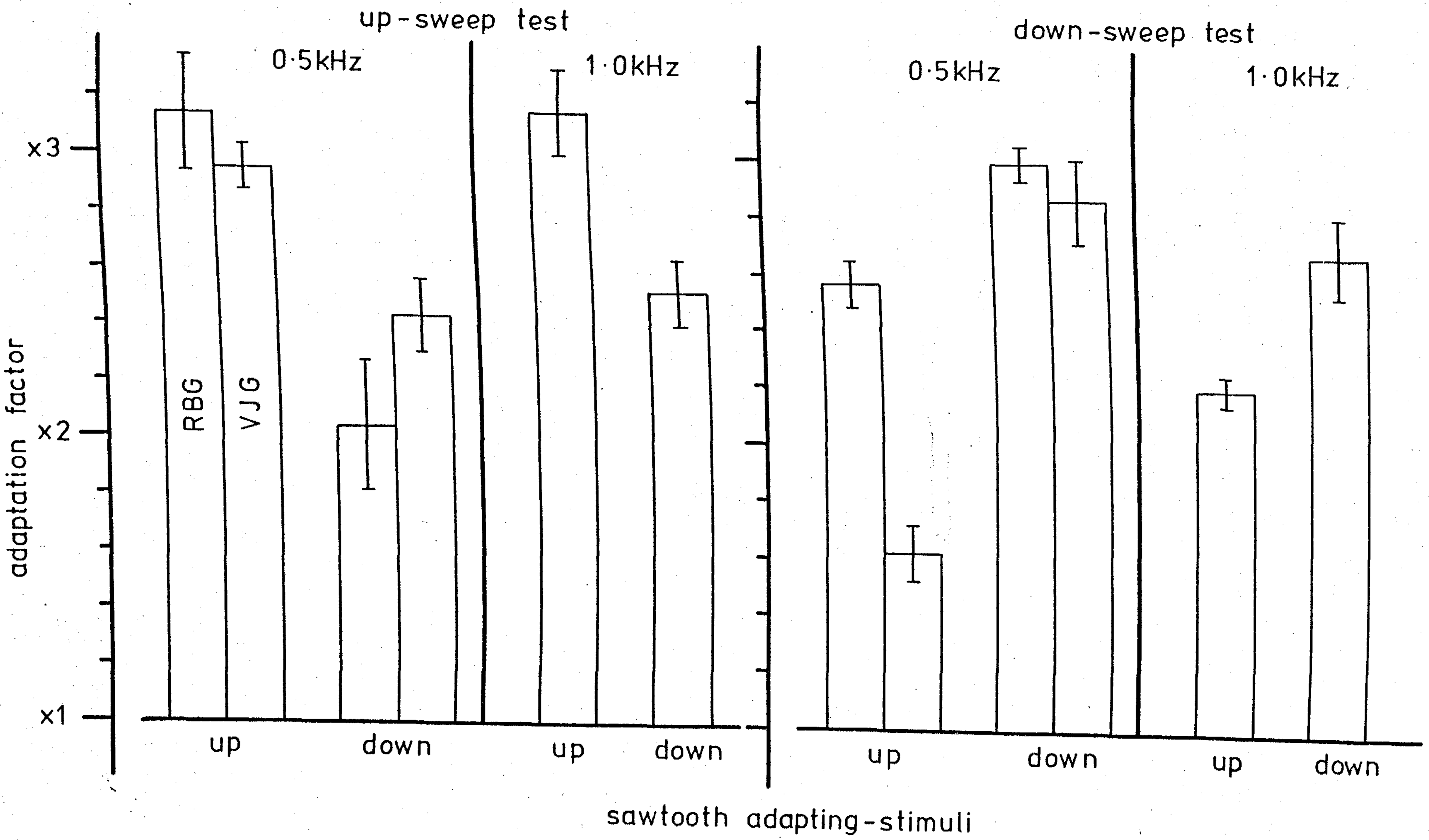
7.5 Single sweep test-stimuli: square-wave-FM adapting-stimuli

This combination of test- and adapting-stimuli allows the adapting effects of rapid FM transitions to be examined.

7.5.1 Methods

Square-wave-FM adapting-stimuli had a frequency-deviation of ±62.5 Hz at 0.5 kHz (RBG and VJG) and at ±80 Hz at 1.0 kHz (VJG). Their modulation-

Fig. 7.3. Histograms of mean adaptation factors for up- and down-sawtooth adapting-stimuli at 0.5 kHz (RBG and VJG) and 1.0 kHz (VJG). Test-stimuli were single linear frequency sweeps (up or down). The modulation-frequency of the adapting stimuli was 8 Hz. Vertical bars are ±1 standard deviation.


up-sweep test
0·5kHz
1·0kHz
down-sweep test
0·5kHz
1·0kHz
adaptation factor
x3
x2
x1
RBG
VJG
up
down
up
down
up
down
up
down
sawtooth adapting-stimuli

frequency was 8 Hz. Test-stimuli were identical to those of the previous section.

7.5.2 Results and discussion

Adaptation factors at 0.5 and 1.0 kHz for the two test conditions are shown in Fig. 7.4. Three threshold estimates were made for each condition and means and standard deviations calculated. Square-wave-FM elevates thresholds for both directions of test sweep, confirming that the rapid frequency transitions of square-wave and sawtooth-FM are effective adapting-stimuli.

7.6 Square-wave-FM test-stimuli

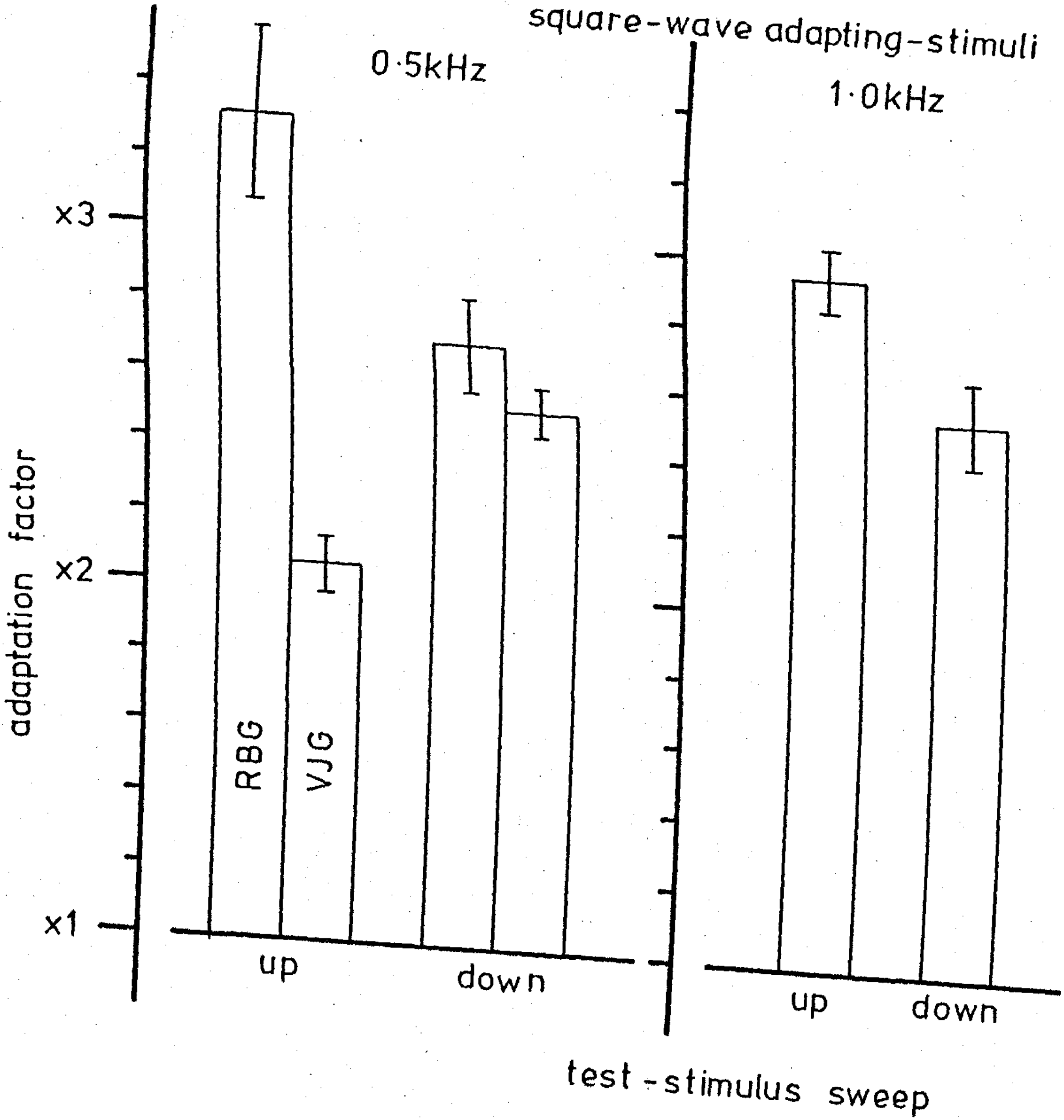
7.6.1 Methods

To examine further the role of rapid frequency transitions in FM-adaptation, square-wave-FM test-stimuli were used with up-sweep and down-sweep adapting-stimuli. Adapting-sweeps had durations of 62.5 ms and a repetition-rate of 8 per second. Adapting frequency-deviation was ±62.5 Hz at 0.5 kHz and ±80 Hz at 1.0 kHz (VJG only). The test-stimulus was a single cycle of an 8 Hz square-wave modulating waveform having a duration of 62.5 ms. Tone-bursts with a repetition rate of 8 Hz and a burst duration of 62.5 ms were used as a control stimulus.

7.6.2 Results and discussion

Figure 7.5 shows histograms of the adaptation factor for each adapting-stimulus condition. Three threshold estimates were made in each condition and means and standard deviations calculated. Both directions of FM-sweep elevate the test threshold, tone-bursts do not. The experiments confirm that the rapid frequency transitions of square-wave and sawtooth-FM are processed by the same channels as other FM stimuli. For this reason, sawtooth-FM is <u>not</u> a suitable stimulus for research into the directional-specific processing of FM stimuli.

Fig. 7.4. Histograms showing the effects of a square-wave-FM adapting-stimulus (F_m = 8 Hz) upon single sweep thresholds at 0.5 kHz (RBG and VJG) and 1.0 kHz (VJG). Vertical bars are ±1 standard deviation.


square-wave adapting-stimuli
0·5kHz
1·0kHz
adaptation factor
x3
x2
x1
RBG
VJG
up
down
up
down
test-stimulus sweep

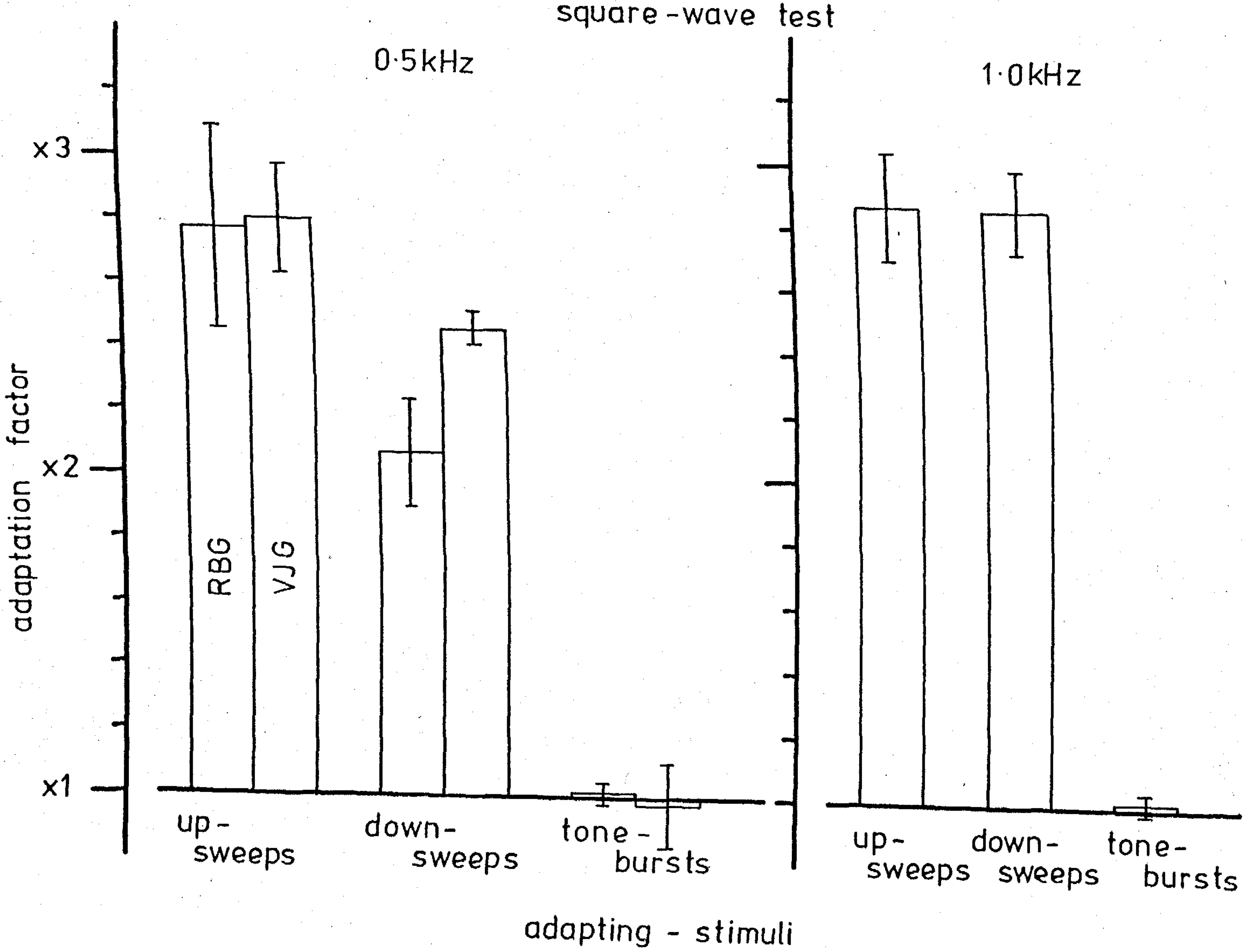
7.7 Summary and discussion

Directional-specificity was established with repetitive linear frequency-sweeps but not sawtooth-FM. This is because sawtooth-FM contains rapid frequency transitions in the opposite direction to the sweep component of the waveform. Because both upward- and downward-going adapting sweeps elevate sawtooth thresholds, sawtooth-FM, like sinusoidal-FM, must contain two functionally separate FM components, both contributing to the detectability of the test FM. This is also true of square-wave FM. The adapting effects of these rapid transitions was confirmed by using sawtooth and square-wave adapting-stimuli with single sweep test-stimuli. The role of rapid transitions in the detectability of test FM was confirmed with square-wave FM test-stimuli.

The fact that the system responds to rapid transitions confirms that the tuning of FM channels to rate-of-change of frequency is rather broad. However, the test-stimulus characteristics do determine adaptation to some extent. Thus, in the data of Fig. 7.1, 7.2 and 7.5, the adapting-stimulus characteristics are constant and the differences in adaptation factors between the figures for a particular adapting-stimulus must be due to the test stimulus.

The effect of the context of the rapid frequency transitions can be seen in Fig. 7.3 and 7.4. Here, test-stimuli are single sweeps and the adapting-stimuli are sawtooth-FM (Fig. 7.3) or square-wave-FM (Fig. 7.4). The only difference between the experiments from the point of view of the rapid transitions is their context. All other relevant test- and adapting variables are constant. Thus the effects of down-sawtooth upon the up-sweep test in Fig. 7.3 is due to the upward-going rapid transition of the sawtooth-FM. The effect of square-wave-FM upon up-sweep test thresholds in Fig. 7.4 must also be due to the upward-going rapid transition. The large difference in adaptation factor between these two conditions reveals

Fig. 7.5. Histograms of mean adaptation factor for various adapting-stimuli at 0.5 kHz (RBG and VJG) and 1.0 kHz (VJG) (F_m = 8 Hz). The test-stimulus was a single cycle of an 8 Hz square-wave modulating waveform with a duration of 62.5 ms. Vertical bars are ±1 standard deviation.


square-wave test
0·5kHz
1·0kHz
adaptation factor
x3
x2
x1
RBG
VJG
up-sweeps
down-sweeps
tone-bursts
up-sweeps
down-sweeps
tone-bursts
adapting - stimuli

the effect of adapting sweep context. Similar differences also exist in the effects of downward-going rapid transitions. The data indicate that, in general, rapid transitions are more effective in the context of square-wave FM than sawtooth-FM. Rapid transitions are discussed in more detail in Chapter 9.

The data of Fig. 7.3 also show that the sweep component of sawtooth-FM is always a better adapting stimulus than the rapid transition component. Thus, for a particular direction of test sweep the greatest adaptation is found when the sweeps of the adapting sawtooth-FM are in the same direction. When sweeps are in the opposite direction and adaptation is due to the rapid transitions, the effect is reduced. In the context of square-wave-FM, these rapid transitions equal sweeps in their effectiveness.

Green and Kay (1973; 1974) have found both square-wave FM and AM to be effective adapting-stimuli. The effectiveness of rapid amplitude transitions means a simple explanation of the Rutland (1976) AM-illusion is impossible. In this experiment a constant amplitude test-stimulus appeared to have a changing amplitude following exposure to sawtooth-AM adapting-stimuli. The apparent change in direction was in the opposite direction to the adapting <u>sweep</u> components and continuous (i.e. sawtooth period was not represented in the illusion). If rapid transitions can also adapt AM channels, then the explanation of the illusion in terms of the relative outputs of directional-specific channels is impossible unless a dissociation between mechanisms involved in threshold elevation and illusions exists. However, if rapid transitions of amplitude are less effective than sweeps in the context of sawtooth-AM, as in the case for sawtooth-FM (above), the sweep adapted channel would be the more adapted and the output of the opposite channel would be relatively higher, thereby producing the illusion. A stronger illusion would be expected if AM sweeps separated by silent gaps were the adapting stimulus.

Tansley and Regan (1980) is a foot-note to their paper criticise Gardner and Wilson (1979) for not using an AM control stimulus when looking for directional-specific FM effects. Given the effectiveness of rapid amplitude transitions (Green and Kay, 1974) the tone-burst stimulus would provide such a control. No adaptation to this stimulus occurred (also see Chapter 6 experiments with single sweep FM test-stimuli) from which it can be concluded no AM adaptation of FM thresholds occurred, i.e. the possibility of cross-adaptation was excluded.

CHAPTER 8

8.1 Introduction

This chapter is concerned with unadapted thresholds which are compared with values of threshold from other studies. The relationship between threshold and test-stimulus duration is also examined.

8.2 Unadapted thresholds: periodic-FM

Most periodic-FM test-stimuli were sinusoidal-FM, however, triangular-FM, sawtooth-FM, repetitive linear frequency-sweeps and square-wave-FM were also used. Thresholds expressed as $\pm\Delta F/F_c\%$ are presented in Table 8.1. Figure 8.1 shows 8 Hz sinusoidal-FM thresholds as a function of F_c. The shape of the curve is, in general, in accordance with the findings of other workers (Shower and Biddulph, 1931; Jestaedt and Sims, 1975; Fastl, 1978). Figure 8.2 shows the same data together with data from other studies using 8 Hz periodic-FM at values of F_c used in this study (Feth, Wolf and Bilger, 1969; Kay and Matthews, 1972; Jestaedt and Sims, 1975). Thresholds are of the same order of magnitude as those found by these studies.

8.3 Unadapted thresholds: single linear frequency-sweeps

Figure 8.3 shows values of threshold for both upward- and downward-going single linear frequency-sweeps of 62.5 ms duration as a function of F_c. A similar function to that for sinusoidal-FM is found. The threshold for down-sweeps is markedly higher than that for up-sweeps for both Ss (Table 8.2). Values of threshold are within the range found by other workers at similar sweep durations (Nabelek and Hirsch, 1969; Tsumura, Sone and Nimura, 1973). Arlinger et al (1977) report linear sweep thresholds to be no greater than those for sinusoidal-FM unlike the present study where linear sweep thresholds are always in excess of sinusoidal-FM thresholds. They also failed to find differences between up- and down-sweep thresholds at 1.0 kHz. Tsumura, Sone and Nimura (1973) found a small difference in

Fig. 8.1. Unadapted thresholds for 8 Hz sinusoidal-FM as a function of F_c for RBG (solid lines) and VJG (dotted lines). The upper graph shows thresholds expressed as $\pm\Delta F/F_c\%$, the lower thresholds as $\pm\Delta F$ (Hz).

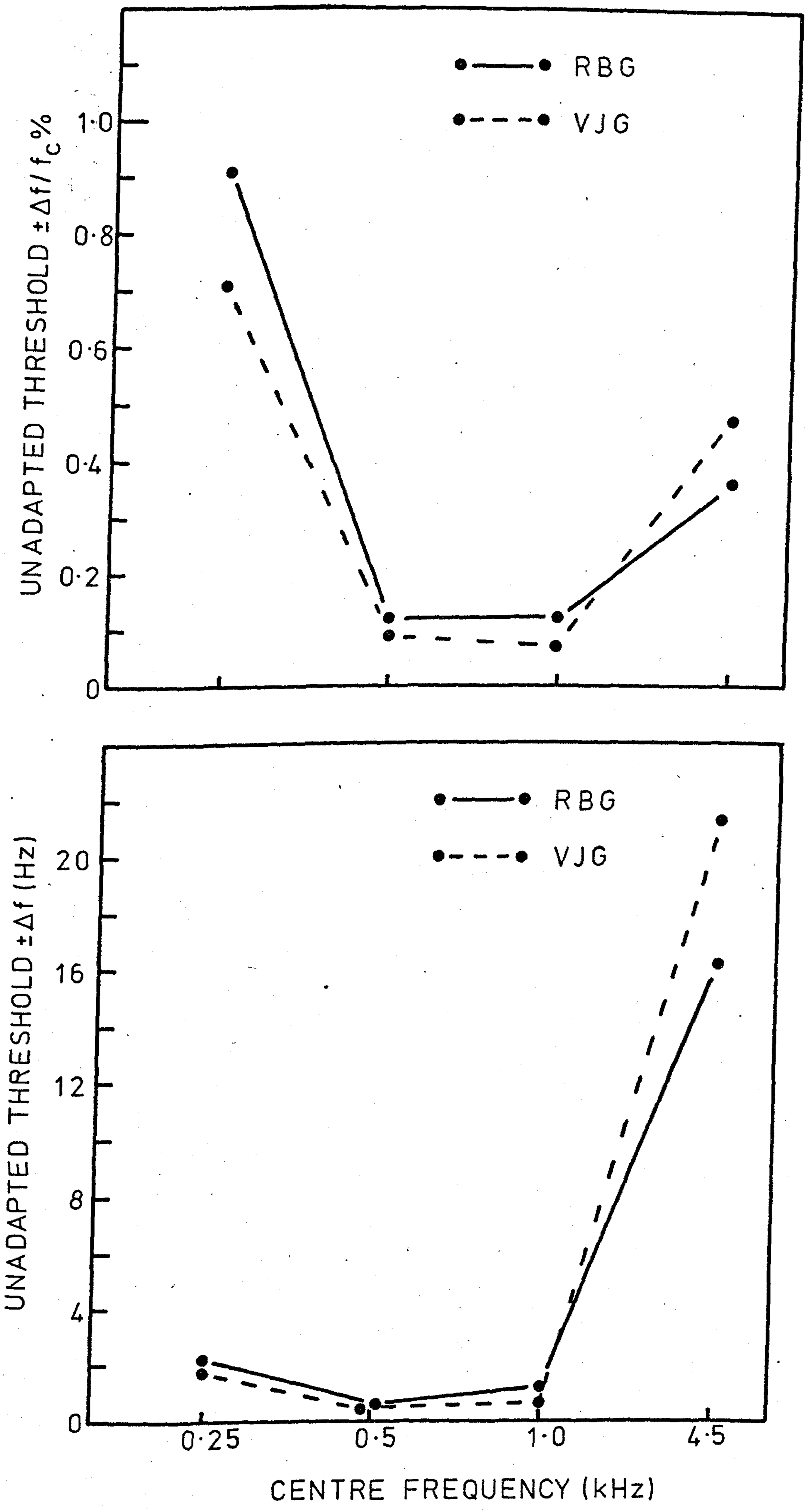
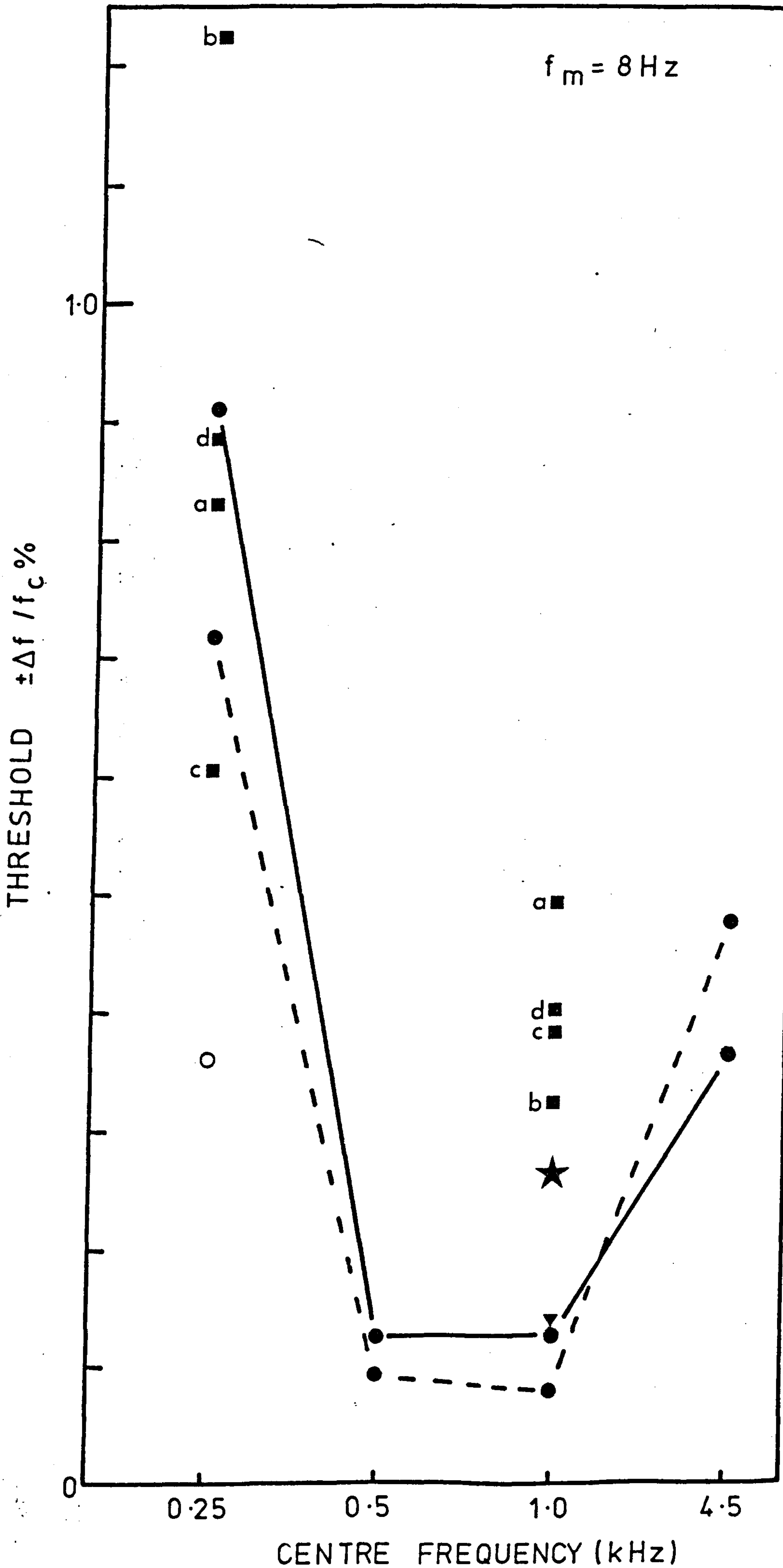

RBG
VJG
UNADAPTED THRESHOLD ±Δf/f$_c$%
0
0·2
0·4
0·6
0·8
1·0
RBG
VJG
UNADAPTED THRESHOLD ±Δf (Hz)
0
4
8
12
16
20
0·25
0·5
1·0
4·5
CENTRE FREQUENCY (kHz)

Fig. 8.2. Unadapted thresholds, expressed as $\pm\Delta F/F_c\%$, for 8 Hz sinusoidal-FM as a function of F_c with thresholds from other studies for comparison. The solid line is data for RBG and the dotted line is data for VJG.

The key is as follows:

■ a-d	Jestaedt and Sims (1975) 8 Hz sinusoidal-FM at 0.25 and 1.0 kHz. Four subjects (a-d). 2IFC procedure.
○	Kay and Matthews (1972) 8 Hz sinusoidal-FM, 0.25 kHz. Method of adjustment.
★	Feth et al (1969) 8 Hz sinusoidal-FM at 1.0 kHz. Method of adjustment.
▼	Feth et al (1969) 8 Hz triangular-FM at 1.0 kHz. Method of adjustment.

Differences in paradigm which introduce an additional factor when comparing these thresholds (see Jestaedt and Sims, 1975).


f m = 8 Hz
THRESHOLD ±Δf / fc %
1·0
0
0·25
0·5
1·0
4·5
CENTRE FREQUENCY (kHz)
b
d
a
c
a
d
c
b

threshold but in the opposite direction to that found here. An explanation of these discrepancies may be derived from an examination of the stimuli employed by Arlinger et al (1977) and Tsumura, Sone and Nimura (1973). These stimuli consisted of frequency transitions with constant frequency segments at the initial and final frequency of the transition. For some subjects the task might become one of detecting the frequency difference between steady-state segments. This might account for the size of Arlinger et al's (1977) thresholds which are consistent with pitch DLs found with steady-state stimuli (e.g. Moore, 1973a;Wier, Jestaedt and Green, 1976). The fact that with similar stimulus configurations the thresholds of Tsumura, Sone and Nimura (1973) and Nabelek and Hirsch (1969) are so much larger than Arlinger et al's (1977) may be explicable when one considers the finding of Fastl (1978) that for pulsed-tone DLs, individual differences of up to a factor of 27 exist compared to a factor of 4 for periodic-FM.

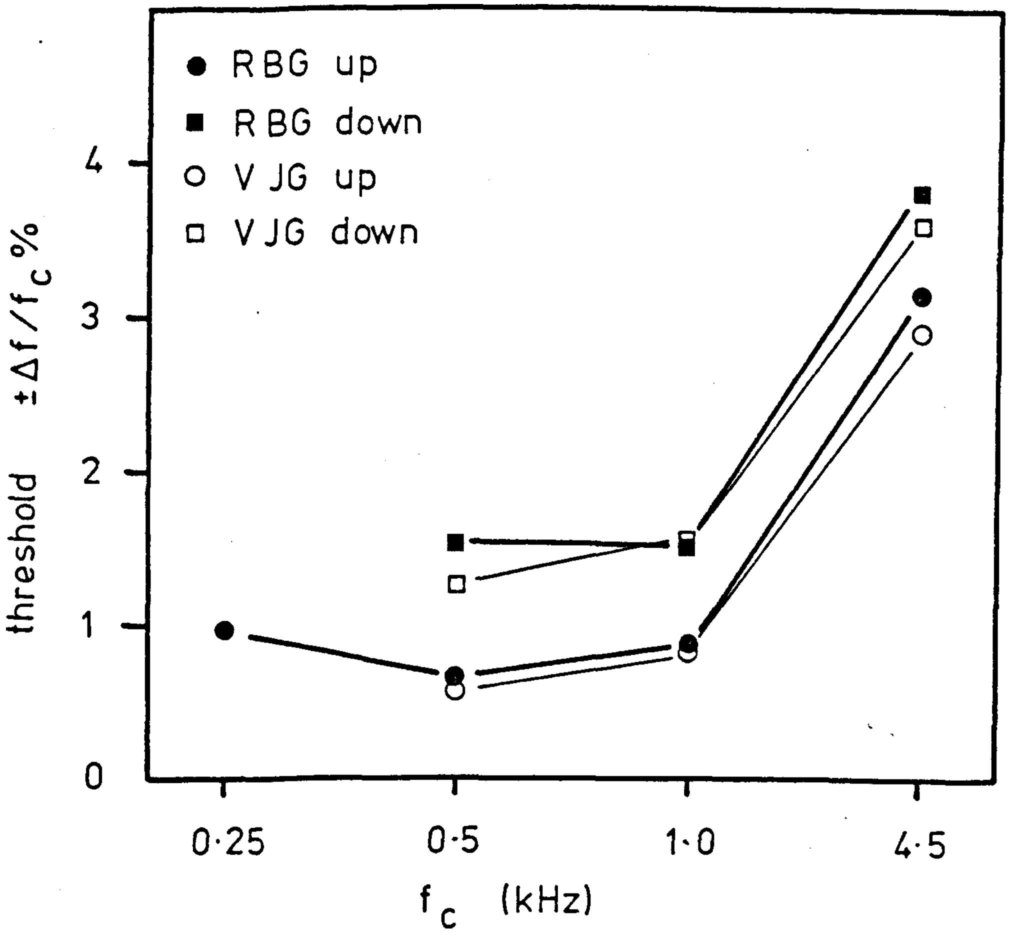
It would seem that isolated single frequency sweeps are the best stimuli for measuring the frequency DLs of frequency transitions.

8.4 Directional-specificity

From the relationship between up- and down-sweep thresholds (Fig. 8.3) it seems that the sensitivity of the down-channel is less than the up-channel. In other words the down-sweep test-stimuli must have a higher ±ΔF (with constant duration) in order to induce the threshold level of activity in FM-channels. It follows that when up- and down-sweeps have the same values of ±ΔF and duration the induced activity, determined by these two variables (see Chapter 3 and Appendix C), is greatest in the up-channel.

Recently, Collins and Cullen (1978) have found up-sweep stimuli are detected at lower intensities than down-sweep stimuli, a difference in sensitivity in the same direction as that found for FM thresholds in this study. At 1.45 kHz the difference was only found for stimulus durations

Fig. 8.3. Unadapted thresholds, expressed as $\pm\Delta F/F_c\%$, for 62.5 ms up- and down-sweeps as a function of F_c. See figure for key.


● RBG up
■ RBG down
○ VJG up
□ VJG down
threshold ± Δf / f_c %
0
1
2
3
4
0·25
0·5
1·0
4·5
f_c (kHz)

below 35 ms at 0.45 kHz, however, the difference extended beyond 90 ms. To account for this difference in sensitivity the authors discussed a model in terms of the temporal distribution of displacement maxima on the basilar membrane. These would be more dispersed for falling glides leading to a smaller number of afferent fibres responding within a certain time compared to rising glides where less dispersion would occur. The effects would be greater at lower frequencies and the difference is afferent activity to rising and falling glide stimuli would occur over a greater range of stimulus durations. If this mechanism played a role in the differences between up-sweep (glide) and down-sweep FM thresholds the difference in threshold might be expected to decrease with increasing F_c. As Table 8.2 shows the relative difference between thresholds does in fact decrease at higher values of F_c. It is possible, therefore, that the mechanism determining differences in sensitivity between up- and down-sweep stimuli has a role in the difference in FM thresholds between these stimuli. The afferent activity generated by the sweep stimuli must provide the input to FM-specific channels in which case if $\pm\Delta F$ and duration are equal up-sweep activity might be expected to be greater than down-sweep activity. This model is only applicable to short duration sweep stimuli whereas Fig. 8.5 shows the difference in threshold between up- and down-sweeps is present over a wide range of durations at 1.0 kHz. It must also be noted that Collins and Cullen (1978) used glides of 500 Hz much wider than the FM threshold values of this study.

It is possible that the difference in threshold is a property of the detection stage of the FM processing system (see Fig. 6.5) rather than reflecting a peripheral mechanism before FM specificity is established. If the difference in threshold is established below FM specific channels then the findi that adaptation to up-sweeps is usually greater than adaptation to down-sweeps (Fig. 3. ; Fig. 6.3; Fig. 6.4) is easily explained in terms of the difference in activity generated by these stimuli in subsequent FM-channels. If the difference in threshold reflects a property of the detection stage then up- and down-sweep adaptation might be expected to be equal, a situation occurring less frequently than differing adaptation. Whatever the mechanism the concept of differing sensitivities of up- and down-channels to particular sweep parameters must be introduced to account for equal or greater down-sweep adaptation if a pre-FM-specific mechanism is involved or differing adaptation if the detection stage alone determines differs in threshold. As Appendix C shows, the relationship between up- and down-sweep adaptation changes as a function of sweep duration (and therefore rate-of-change of frequency) when ±ΔF is constant at 1.0 kHz. Though FM-channels must be broadly tuned to df/dt, it is possible that these broad tuning characteristics differ between up- and down-channels as a function of F_c.

Sawtooth-FM produces some interesting problems, in that up-sawtooth thresholds are lower than down-sawtooth thresholds (Table 8.1). If it were not known that the rapid frequency transitions of these stimuli also contributed to the detectability of sawtooth-FM (Chapter 7), then the difference in threshold would not be surprising given the relationship between single sweep thresholds of different direction. However, the presence of the rapid transitions in the modulation waveform would be expected to decrease or remove this difference in threshold between the two sawtooth waveforms. It must be assumed that rapid transitions contribute less to detectability than the sawtooth sweep. This is supported to some extent by the finding that adaptation produced by the rapid transitions of sawtooth-FM is always less than adaptation to a sawtooth-sweep in the same direction (e.g. the difference between up-sawtooth and down-sawtooth adaptation of up-sweep thresholds in Fig. 7.3). As discussed in Chapter 7, rapid transitions in sawtooth-FM are less effective adapting-stimuli than identical transitions in square-wave-FM. In the context of sawtooth waveforms, their contribution to detectability might also be reduced. In a situation where sweeps and rapid transitions are presented together the FM channels may respond preferential to sweeps with a greater likeness to formant transitions.

8.5 The relationship between unadapted-threshold and test stimulus duration

8.5.1 Methods

The main body of the experiment was carried out at 1.0 kHz with triangular -FM, single up-sweep and single down-sweep thresholds. Experiments were also carried out at 0.25 and 0.5 kHz with 8 Hz triangular-FM. Only one subject, RBG, was used. At 1.0 kHz experiments with triangular-FM were done with values of F_m of 4, 8 and 16 Hz. The experimental variable was the duration of the modulated test interval, the duration of the unmodulated interval being adjusted in each experimental condition to match this value. Adjustments in the duration of the silent gaps were made for test durations below 500 ms to keep the overall duration of the test phase constant. Above 500 ms the duration of the silent gaps was set at 100 ms. Test-stimulus and silent gap durations are given in Table 8.3. Durations of 62.5 ms were used for sweep only, 1000 ms for triangular-FM only.

8.5.2 Results and discussion

Triangular-FM thresholds are shown in Fig. 8.4 and 8.5, sweep thresholds in Fig. 8.6. All thresholds are the means of three estimates. The curves show an exponential relationship between threshold and test-stimulus duration such that threshold decreases as duration increases. A time constant of 400 ms can be derived from the curves. At 1.0 kHz the curves for triangular-FM at different values of F_m are almost identical indicating that the overall duration of the test-stimulus and not the number of cycles of the waveform within the test interval determines periodic-FM thresholds. The difference in threshold between up- and down-sweeps is preserved over the range of stimulus durations used.

Fig. 8.4. Unadapted thresholds, expressed as $\pm\Delta F/F_c\%$, as a function of test-stimulus duration for triangular-FM at 0.5 and 1.0 kHz and for values of F_m of 4, 8 and 16 Hz at 1.0 kHz. See figure for key.

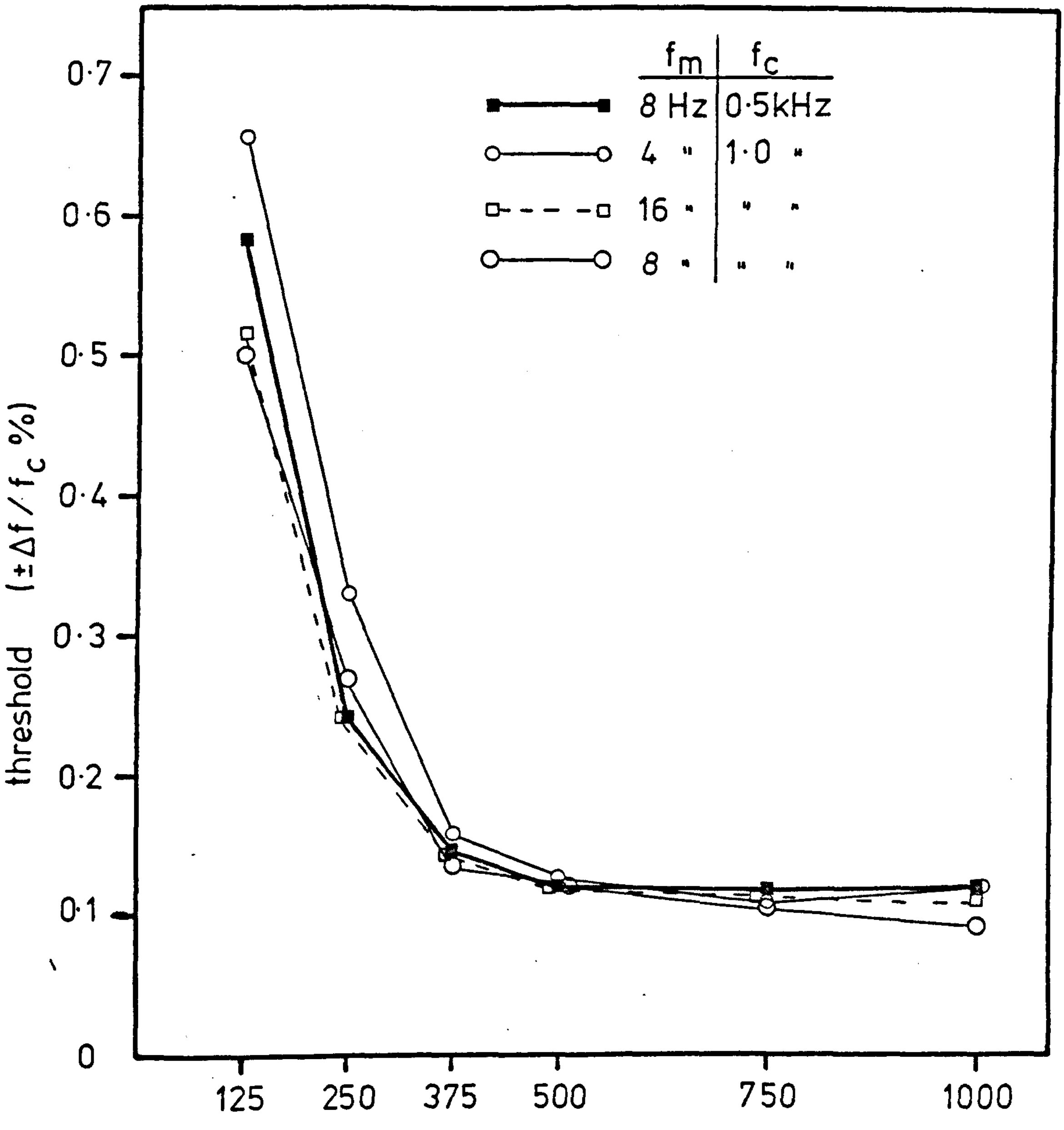
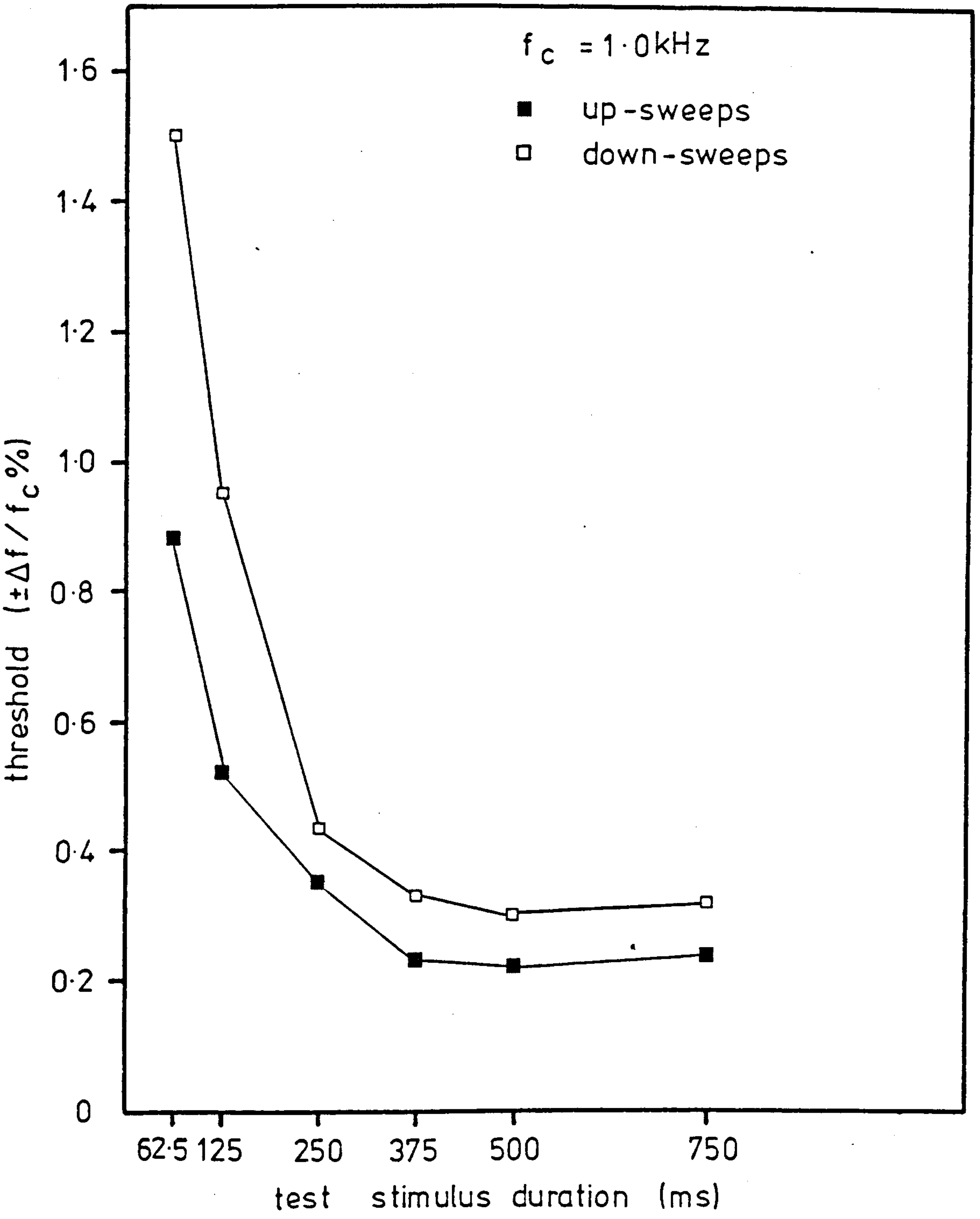

f_m | f_c
8 Hz | 0·5kHz
4 " | 1·0 "
16 " | " "
8 " | " "
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
threshold (±Δf / f_c %)
125
250
375
500
750
1000
test stimulus duration (ms)

Fig. 8.5. Unadapted thresholds, expressed as $\pm\Delta F/F_c\%$, as a function of test-stimulus duration for 8 Hz triangular-FM at 0.25 kHz. See figure for key.


$f_c = 1 \cdot 0$ kHz
■ up-sweeps
□ down-sweeps
threshold ($\pm\Delta f / f_c$%)
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
62·5
125
250
375
500
750
test stimulus duration (ms)

The time constant derived from the curves can be regarded as the integration time of the detection stage of FM-processing. The figure is larger than that found for the detection of FM-stimuli, as opposed to FM, by Collins and Cullen (1978) and most other estimates of integration time for auditory stimuli. The value of the constant is independent of carrier-frequency. If, as seems likely from Chapter 3 and Appendix C, the area under the test-stimulus modulating waveform or sweep (the "FM-energy") determines threshold, then the data show that only the "energy" within the first 400 ms of the stimulus is integrated and determines threshold.

TABLE 8.1

Unadapted thresholds expressed as ±$\Delta F/F_c$% for periodic FM stimuli used in this study

Stimulus and duration		F_m(Hz)	F_c(Hz)	Subject	Mean Threshold (±$\Delta F/F_c$%)
Sinusoidal-FM 500 ms		8	0.25	RBG	0.91
		8	0.25	VJG	0.716
		8	0.5	RBG	0.123
		8	0.5	VJG	0.09
		8	1.0	RBG	0.123
		8	1.0	VJG	0.077
		8	4.5	RBG	0.36
		8	4.5	VJG	0.473
		10	0.25	RBG	0.93
		10	1.0	RBG	0.12
		12	1.0	VJG	0.07
Sawtooth-FM 500 ms	UP	8	0.5	RBG	0.092
		8	0.5	VJG	0.103
		8	1.0	VJG	0.093
	DOWN	8	0.5	RBG	0.206
		8	0.5	VJG	0.18
		8	1.0	VJG	0.158
Repetitive linear sweeps 500 ms	UP	8	1.0	RBG	0.098
		8	1.0	VJG	0.102
	DOWN	8	1.0	RBG	0.183
		8	1.0	VJG	0.168
Triangular-FM 500 ms		8	1.0	RBG	0.12
Square-wave-FM 62.5 ms		8	0.5	RBG	0.66
		8	0.5	VJG	0.58
		8	1.0	VJG	0.62

TABLE 8.2

Thresholds expressed as ±ΔF/F_c% for single-sweep test stimuli

(See Figure 8.3)

F_c (kHz)	RBG UP	 DOWN	 DOWN/UP	VJG UP	 DOWN	 DOWN/UP
0.25	0.96					
0.5	0.65	1.53	2.35	0.56	1.25	2.23
1.0	0.88	1.5	1.7	0.82	1.53	1.86
4.5	3.13	3.8	1.21	2.9	3.6	1.24

TABLE 8.3

Durations of test-stimuli (triangular-FM, single up-sweeps, single down-sweeps) and silent gaps used in the experiment reported in Section 8.5.

Test stimulus duration (ms)	Duration of gaps 1 and 3 (ms)	Duration of gap 2 (ms)
62.5	319	537
125	287.5	475
250	225	350
375	162.5	225
500	100	100
750	100	100
1000	100	100

CHAPTER 9: DISCUSSION AND SUMMARY

9.1 Background to the thesis

The overall plan of the thesis was to provide insight into the auditory processing of complex stimuli and provide a link between conventional psychoacoustical research and speech processing. The experiments and models are firmly planted in theories of pattern recognition through feature analysis, the aim of the experiments being to provide evidence for feature analysis in auditory processing. The success of this approach in the investigation of the visual system, the promising results of Kay and Matthews (1971, 1972) and the use of pattern recognition theories of pitch processing (Terhardt, 1974b; Wilson, 1974) made the investigation quite attractive. Selective adaptation techniques provide the best existing psychophysical tool for the study of feature analysis allowing the experimenter to examine the part of the auditory system concerned with the feature in question. What is examined is the subjects processing and detection of FM as a distinct feature of FM stimuli. The test stimulus, or more precisely, the test modulation, can be considered as the probe introduced into channels specific for FM. The unadapted threshold gives the base-line measure of the system's sensitivity to FM. Elevations of threshold after exposure to adapting stimuli reflect changes in state of FM-channels measurable as changes in sensitivity to test modulations.

9.2 Main findings

These are as follows:

(a) The relationship between adaptation factor and frequency-deviation (±ΔF) found in Chapter 3. This is consistent with the existence of a Gaussian filter in the carrier-frequency (F_C) domain. Excursions beyond the filter resulted in a decline in adaptation possibly due to lateral inhibitory side-bands of the filter. For values of ±ΔF less than or equal to the effective filter bandwidth, a quantitative description of adaptation was provided by the integral of the modulating-waveform. This accounted for the rise in adaptation with increasing ±ΔF of sinusoidal-FM transitions of constant duration (Fig. 3.1). This model was tested and confirmed by using linear-sweep adapting stimuli of constant duration and variable ±ΔF (Fig. 3.6). Thus when the duration of a transition is constant, linear relationship exists between adaptation factor and adapting ±ΔF. The number of repeats (overall duration) of an adapting stimulus must also be an important variable. For instance, using small frequency deviations Regan and Tansley (1980) found much larger adaptation factors than those found in the present study with comparable stimuli. Regan and Tansley (1980) adapted for 20 minutes however.

(b) Large differences between Gaussian bandwidths, which can be considered as a measure of the F_c-selectivity of the system, and F_c tuning-curves were found in Chapter 4. On the basis of the results of Chapter 5 concerning the mechanism of adaptation the difference was consistent with a two-stage model of F_c-selectivity in FM-channels. The wider Gaussian bandwidths represent the selectivity of the system at the input stage, i.e. the range of frequency-tuned (probably direction-specific) channels (or fibres) activating a particular channel at the frequency-selective level (Fig. 6.6). The closeness of Gaussian bandwidths to critical bandwidths and the similar functions with respect to frequency (Fig. 3.9) suggest they are measures of general auditory frequency selectivity based on a common mechanism. The lateral inhibitory side-bands of the Gaussian filter could represent processes at this level of selectivity analogous to "lateral suppression" effects in masking (Houtgast, 1972; 1974; Shannon, 1976; Terry and Moore, 1977). Alternatively, it may represent the activation of "releasing" channels at the frequency-tuned channel level. Tuning-curves represent a second stage of frequency selectivity at the level at which adaptation occurs. They represent the range of FM-channels having an adapting influence upon the test channel where adaptation is an after-effect of prolonged inhibition of a channel by adjacent channels. The bandwidth of frequency selectivity revealed by tuning-curves is rather narrow and better than measures of pure-tone frequency selectivity as revealed by critical-bands (Scharf, 1971). Neurophysiological data (Whitfield and Evans, 1965) shows that the opposite is true in the case of FM-specific neurones where wider bandwidths are usually found.

(c) As discussed above the mechanism of adaptation was found to be lateral-inhibitory connections between tuned-channels in both the F_c and F_m domains. The range of adapting inhibitory connections determined both F_c and F_m tuning-curve bandwidths. Facilitation effects were consistent with an "inhibition of inhibition" or "releasing" effect produced by channels not directly connected to the test channel. The visual precedent of the experiments of Chapter 5 (Dealy and Tolhurst, 1974) had supporting neurophysiological evidence for inhibition between feature detectors (e.g. Blakemore and Tobin, 1972). No such data exists to support the auditory model. However, specific predictions are generated concerning interactions between, for example, F_m tuned neurones in the auditory cortex of the cat (Jolley, cited in Evans, 1974). This level of processing, referred to as the frequency-selective level, can be considered as a two-dimensional array of tuned channels defined by preferred F_c and F_m. Tuning-curves as measured must represent the resultant function of a complex of inhibitory interactions at this level.

(d) The existence of direction-specific adaptation points to a division of FM-channels into two major sub-channels below the level at which adaptation occurs. It was necessary to assign each direction-specific channel a separate frequency selective level of processing (Fig. 6.6). Directional-specificity is the fundamental division or "critical-boundary" within FM-specific channels. The immunity from cortical ablations of the discrimination of rising from falling sweeps in the cat (Kelly and Whitfield, 1972) is consistent with the early establishment of direction-specificity in sensory pathways. This specificity might arise from an exploitation of the direction preferences of neurones at lower levels of the auditory pathway (see Section 1.3.1). At higher levels direction-specific rather than preferential neurones are found.

(e) The fact that adaptation affects test thresholds means the test modulation is processed in both direction-specific and F_c- and F_m-selective channels before being detected. The threshold in these terms is the rise in output of a particular channel or channels in the array that can be detected at the measured performance level. Thus detection of test modulation and the identification of supra-threshold FM is based on excitatory activity in FM-channels, the selectivity of adaptation and adaptation itself are determined by inhibitory processes. The integration time of the detection stage was found to be 400 ms and to be independent of F_c.

A number of inconsistencies of the empirical data with the model exist. These are as follows:

(a) Cross-adaptation of FM-thresholds by AM stimuli occurs, as found by other workers (see Section 1.4.1). This is inconsistent with the feature-specificity of FM-channels. The work of Coninx (1978a,b) suggests a role for the equal loudness contour (ELC) in these cross-adaptation effects; the effect of tone-bursts increases with F_c consistent with the steeper slopes of the ELC at higher frequencies found by Coninx (1978a,b).

(b) The model describing the relationship between the integral of the modulating waveform and adaptation would predict increases in adaptation with increasing duration of frequency sweeps. However, the concept that adaptation rises indefinitely with sweep duration (limited of course by the need to maintain a constant repetition rate) is rather simple and not verified empirically. In the 0.25 kHz data of Appendix C, adaptation levels off after 50 ms with a slight decrease occurring for down-sweeps as duration increases. In the 1.0 kHz data the adaptation to down-sweeps is roughly constant over a range of durations. Differences in the form of the functions exist between up- and down-sweeps especially at 1.0 kHz. Thus the temporal factors of the sweep are important and differences exist between up- and down-channels. In Fig. 3.6.6 adaptation to 1600 Hz/s sweeps was either equal or less than 2000 Hz/s sweeps. The model would predict higher adaptation at 1600 Hz/s because the sweep durations are larger for each value of ±ΔF below the filter bandwidth.

The response of the system, as measured by adaptation, shows distinct preferences for the temporal characteristics of FM sweeps. This is confirmed by the finding that test-stimulus waveform characteristics can influence adaptation factors (p.85). This might represent tuning or preferences for values of df/dt. Moller (1974a,b) found CN units to have preferred rates-of-change of frequency and Watanabe and Ogushi (1968) and Watanabe (1972) report preferred rates-of-change of frequency dependent upon the a units directional preference. The successful use of the cosinusoidal weighting function in Chapter 3 also points to the need to consider df/dt. Sergeant and Harris (1962) and Pollack (1968) have shown subjects are capable of detecting small differences in rate-of-change of frequency. However, these results cannot represent the influence of df/dt per se because an increase in adaptation is found when sweep duration is constant and ±ΔF increases (Fig. 3.1, Fig. 3.6) whereas a decrease in adaptation is found when sweep duration is a decreased and ±ΔF held constant (Appendix C). In both cases df/dt is increasing but the effects on adaptation are in opposite directions. Without further data on the role of df/dt ±ΔF and sweep duration can be considered the critical variables of adapting-stimuli. The input stage to the frequency selective stage of processing can be considered as an array of frequency-tuned elements, the activation of which is distributed over time as the frequency of a stimulus changes. The activation of the next level involves summation of this temporally distributed activity. An optimal sweep duration can be conceived representing the time in which maximal summation occurs independent of the bandwidth (±ΔF) of activation.

(c) Rapid frequency transitions were found to adapt FM-channels when on the basis of Appendix C they would be expected to have little effect because of their extremely short durations. A modified version of the Green and Kay (1973, 1974) concept of channels concerned with the waveform of modulation might help explain the results. Thus rapid transitions and square-wave-FM could be processed in different channels to sweeps but still have access to the frequency-selective stage of FM-processing, hence sweeps adapt rapid transitions and vice-versa. Whereas sweep induced activity is given by the area under the modulating waveform, the activity generated by rapid transitions in FM-channels might be described by ±ΔF only. This might account for the effect of context of rapid transitions found in Chapter 7. In the context of sawtooth-FM, i.e. sweeps, the specification of ±ΔF might be impaired compared to square-wave-FM with its constant frequency segments.

(d) As discussed above, adaptation experiments reveal preferences based on the temporal characteristics of adapting sweeps. Thresholds for single frequency sweeps as a function of sweep duration reveals an integration time of 400 ms at the detection stage of the system. Thus two distinct temporal processes seem to exist for the processing of sweeps.

The main body of the data support the general scheme of the model of Fig. 6.6. A wide range of further experiments are suggested, especially into the role of temporal factors (other than repetition rate and modulation-frequency) in adaptation and detection.

9.3 The role of FM-channels

Psychophysical evidence is provided for auditory feature analysis in the form of channels selectivity responsive to FM and tuned to limited ranges of the dimensions defining this modulation. An important question is the role of these channels in the coding of naturally occurring sounds. The experiments deal with the detection of small frequency transitions whereas FM-channels, if they have a role in speech processing, must deal mainly with supra-threshold FM in the form of formant transitions and intonation contours. Though it is possible that the properties of the system discovered in the thesis are exclusive to the threshold task, it is hoped they have some function in normal situations. Further, adaptation can be regarded as an artificially created by-product of FM-channels, in that, the stimulus regime of the experiments does not occur naturally. The system is stimulated into an abnormal state reflecting the after-effects of prolongation of processes whose normal function is the coding of FM.

The inhibitory connections between channels can be regarded as a sharpening mechanism that reduces activity in channels adjacent to the F_c or F_m channel increasing its relative output. Because of the limits imposed on ±ΔF by F_c selectivity, frequency-deviation cannot be fully coded in the output of a particular channel. The full specification of ±ΔF may involve the extent of activation across the array of channels.

Though experiments have confirmed, with some ambiguity, a role for frequency transition in speech processing (Section 1.2 and 1.7.2), it is hard to see any need for channels coding the properties of centre-frequency (as opposed to an initial and terminal frequencies which would also give the frequency deviation) and modulation-frequency. The latter is especially interesting in that it is hard to see any role in speech perception for channels coding this feature which is not a common feature of speech sounds.

Channels tuned to F_m seem to be acting as counters having preferred rates of arrival of sweeps.

If the properties of FM channels have a functional basis and are important in the processing of naturally occurring frequency-modulations then the experiments point towards directions for research into the important variables of FM in speech.

The evolutionary development of feature-analysis systems, the neurophysiological reality of which is well established (see Evans, 1974; Scheich, 1976) can be regarded as an alternative to the exhaustive specification of sensory input. Feature-specific channels allow the classification of stimuli according to features having significance for the species. The codification of stimulus patterns is only of value when mechanisms capable of analysing the code exist or arise through ontogenetic sensory experience.

9.4 Methodological shortcomings

The main problem was the time taken for a single threshold determination which was about 45 minutes. Because auditory selective adaptation was a relatively recent discovery, it was felt necessary to carry out at least three threshold estimates in each experimental condition. The standard deviations obtained suggest one threshold estimate per condition would be sufficient. This would reduce by two-thirds the time taken for a threshold determination. By exploring different paradigms and adaptation times, a rapid method might be developed allowing the effects to be studied in a larger population of subjects.

9.5 Conclusions

1. Evidence is provided for the existence of channels in the human auditory pathway selectively responsive to frequency-modulation.

2. Support is found for an essential low-level division of these channels into those coding up-sweeps and those coding down-sweeps.

3. A higher level division of direction-specific channels into channels responsive to limited ranges of carrier- and modulation-frequency is indicated. Evidence for these channels takes the form of tuning-curves representing the range of adapting carrier- or modulation-frequencies that elevate (or facilitate) the threshold of a fixed carrier- and modulation-frequency test-stimulus.

4. Support is provided for the hypothesis that adaptation is an after-effect of prolonged inhibition of a channel by self-inhibition and lateral inhibition from surrounding channels. In these terms tuning-curves represent the range and strength of lateral-inhibitory connections between channels.

5. The experimental results are consistent with a two-stage model of F_c selectivity. The first level is given by a Gaussian filter, closely related to the critical band, the existence of which was inferred from functions of adaptation factor versus adapting frequency deviation given in Chapter 3. The second stage is represented by F_c-tuning curves.

6. Adaptation produced by sweeps of constant duration was found to be directly proportional to ±ΔF when the value of ±ΔF is less than the effective Gaussian filter bandwidth.

7. Preferences for the temporal characteristics of sweeps are found.

8. Detection of FM occurs after feature-specific processing or alternatively, as a consequence of this processing.

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APPENDIX A

The derivation of formula for the area under a sinusoidal waveform when the frequency deviation is in excess of the hypothesised filter bandwidth is given below.

$$A = \int_{o}^{z} a \sin x \, dx$$

where A is the area

z is the intercept on the x (time) axis from the point where the waveform crosses the filter boundary (see Fig. 3.)

a is the amplitude expressed as ±ΔF (Hz).

$$= a[-\cos x]_{o}^{z}$$

$$= a(-\cos z + \cos o)$$

$$= a(1 - \cos z)$$

$$= a - a\cos z$$

where $a\cos z = a\sqrt{1-\sin^2 x}$

$$(a\cos z)^2 = a^2 \times (1 - \sin^2 z)$$

$$a\cos z = \sqrt{a^2 - a^2 \sin^2 z}$$

where $b = a \sin z$

$$a \cos z = \sqrt{a^2 - b^2}$$

$$A = a - \sqrt{a^2 - b^2}$$

APPENDIX B

It is possible that adaptation may persist for some time leading to spurious estimates of elevated thresholds.

As reported in Chapter 2, two or three threshold estimates are made at each stimulus condition, a data point being the mean of such a series. The time between estimates is 3-5 minutes. This is longer by over a factor of three than the decay time of adaptations reported by Kay and Matthews (1972). Adaptation was found to be almost zero after one minute, at least at 250 Hz, following a 12 second exposure to the adapting stimulus. This suggests that persistence does not occur over the time between threshold estimates of the present study. However, because of differences in subjects, psychophysical procedures, stimulus conditions and carrier frequencies, it was felt that the possibility of persistence was worth studying.

As stated above, the time between threshold estimates for a single stimulus condition was between three and five minutes. The time between estimates for different stimulus conditions was usually longer than ten minutes. Any persistence should thus be observable within a series of adapted threshold estimates for a single stimulus condition (data point). If persistence was present one would expect that within a three estimate series the third estimate would yield a higher threshold than the second which would in turn be higher than the first. Since thresholds were recorded in the order in which they were obtained, it is possible to test this prediction.

A sample of 45 mean adapted thresholds (135 (45 x 3) threshold estimates) were analysed. Pairs of threshold estimates compared for each mean adapted threshold were 1 and 2, 1 and 3 and 2 and 3. The persistence hypothesis predicts the latter threshold of each pair would be higher. For each pair the following calculations were made.

(a) % of sample in which the second threshold was higher than the first.

(b) % of sample in which the second threshold was lower than the first.

(c) % of sample in which the second threshold was equal to the first.

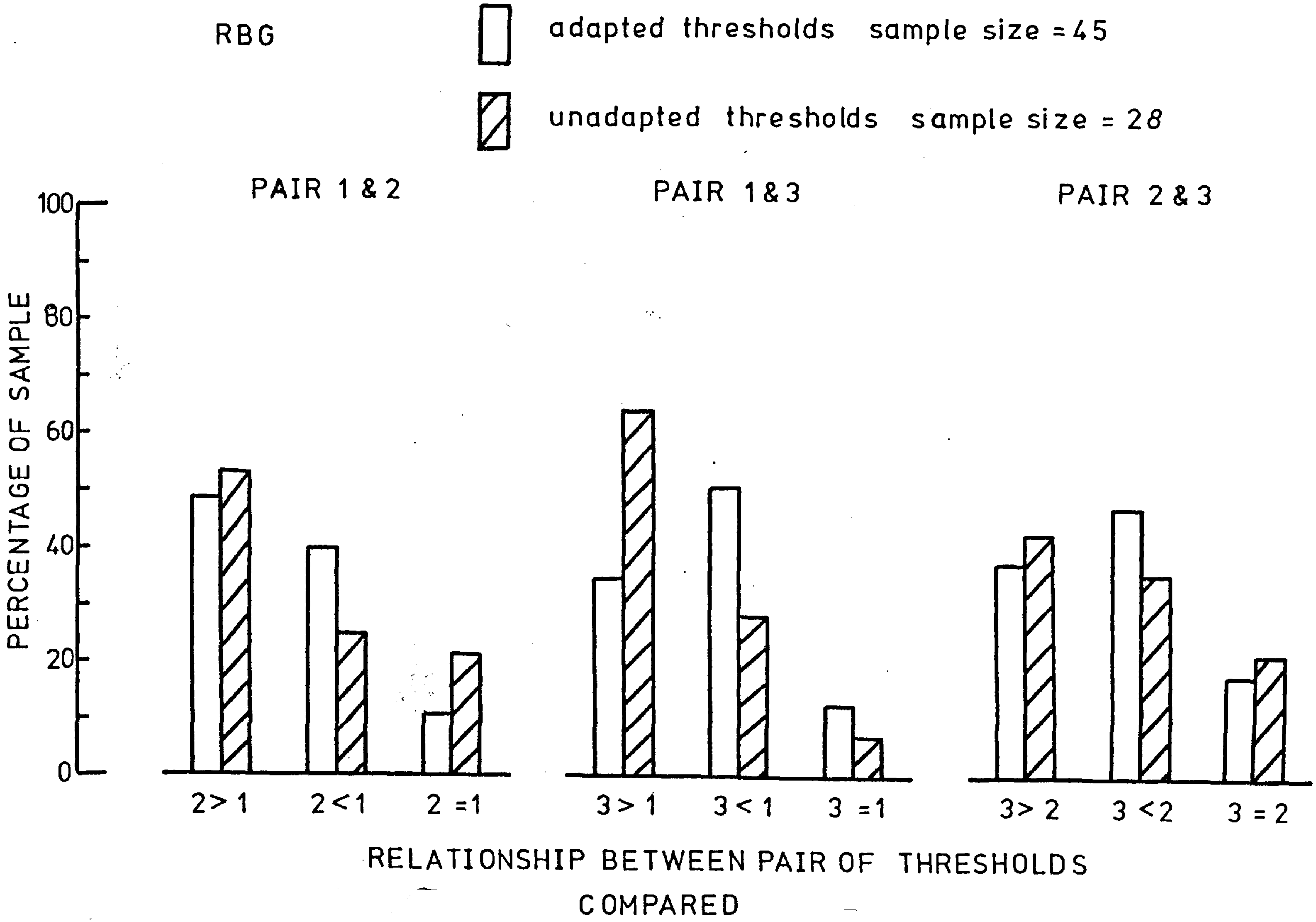
A sample of 28 unadapted thresholds were also analysed as a control.

Samples included thresholds at different frequencies and different stimulus conditions. There was no a priori reason to assume that persistence would be frequency or stimulus condition specific. An analysis of the samples by stimulus condition (both test and adapting stimuli) revealed no such specificity, that is, the trends of the data of Fig. 8 discussed later were not specific to a certain stimulus condition.

Data are shown in Figure 8. The persistence hypothesis would predict that a greater percentage of the sample would conform to (a) above. The trend seems to be in the opposite direction for pairs 1 and 3 and 2 and 3 where most of the sample conform to (b), i.e. the latter thresholds of these pairs are the lower. The hypothesis that the effect of adaptation persists over a duration of 3-5 minutes or more can be rejected on the basis of this data in which the trend is in the opposite direction to that predicted by the persistence hypothesis.

The unadapted threshold data for all pairs seems to support the persistence hypothesis in that the percentage of the sample conforming to (a) is greater than that conforming to (b). Obviously the data from unadapted thresholds has no bearing upon the validity of the persistence hypothesis. The data can be assumed to indicate a bias towards higher thresholds for the second and third estimates of a series for reasons other than persistence of adaptation (e.g. loss of attention by S, decreased motivation, boredom leading to more erroneous decisions). Such a trend might be expected to be present in the adapted threshold data. Though this

Fig. B1. Graph showing separate data for 45 adapted thresholds and 28 unadapted thresholds (each threshold being the mean of three threshold estimates) in terms of the percentages of the samples conforming to the stated relationships between pairs of threshold estimates within a series. Subject RBG only. Data pooled across frequency (F_c) and stimulus condition.


RBG
adapted thresholds sample size = 45
unadapted thresholds sample size = 28
PAIR 1 & 2
PAIR 1&3
PAIR 2 & 3
PERCENTAGE OF SAMPLE
100
80
60
40
20
0
2>1
2<1
2 =1
3 > 1
3 < 1
3 =1
3> 2
3 <2
3 = 2
RELATIONSHIP BETWEEN PAIR OF THRESHOLDS COMPARED

trend is observed in pair 1 and 2, this is not the case in pairs 1 and 3 and 2 and 3. It can be concluded that no persistence occurs.

The trend in the unadapted threshold, however, data might indicate the presence of an adapting influence of the test-modulation persisting across the separate threshold estimates such that later estimates are higher.

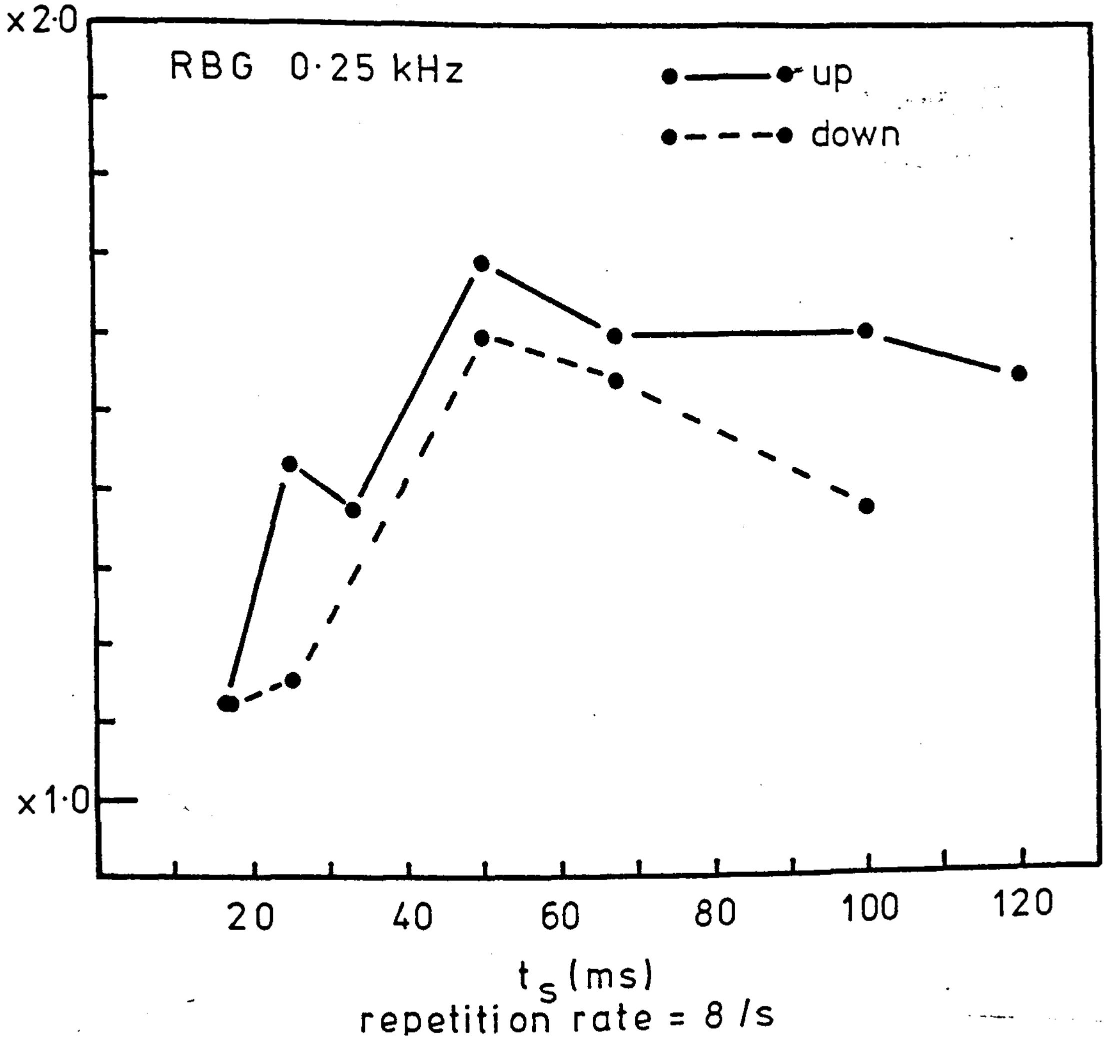
APPENDIX C

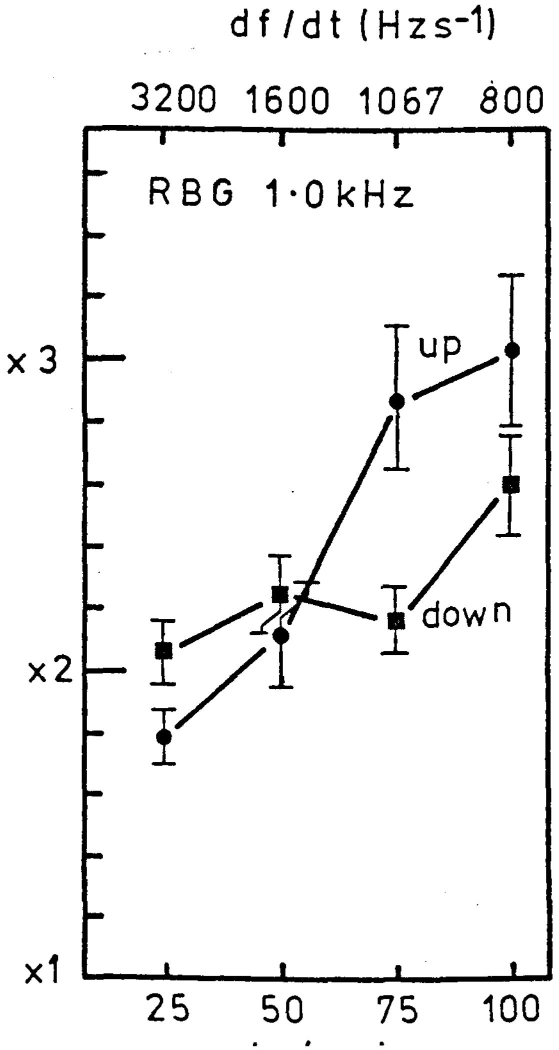
In Chapter 3 the relationship between ±ΔF and adaptation factor was determined and adequately described by the area under the adapting transitions when transition duration was a constant. However, the influence of duration upon adaptation factor when ±ΔF was a constant was not examined. The model of Chapter 3 would predict that adaptation also increased with increasing duration of sweep. This assumption was tested at 0.25 and 1.0 kHz with up- and down-sweep adapting-stimuli with an 8/s repetition rate and an 8 Hz sinusoidal-FM test-stimulus of 500 ms duration. Experiments were carried out for RBG only. At 0.25 kHz the adapting ±ΔF was ±25 Hz at 1.0 kHz this value was ±80 Hz. Three threshold estimates were made in each condition and means and standard-deviations calculated.

Data are presented in Fig. C1. Both curves show a trend of increasing adaptation factor as sweep duration (t_s) increases. At 0.25 kHz the curve flattens out at 50 ms, this was not found at 1.0 kHz. At 1.0 kHz the increase for down-sweeps (squares) is less marked than the increase for up-sweeps. The general trend confirms that predicted rise in adaptation as duration increases with ±ΔF constant, i.e. as the area under the sweep increases. However, a major problem exists, in that, Chapter 7 shows rapid frequency transitions to produce large elevations of threshold. Extrapolation from the curves of Fig. C1 would predict little adaptation with such transitions, i.e. high rates-of-change of frequency. This is discussed in Chapter 9.

Figure C1 shows that at 1.0 kHz the relationship between up- and down-sweep adaptation changes is a function of t_s. This indicates the broad tuning of up- and down-channels to df/dt differs (see Chapter 8).

Fig. C1. Adaptation factor as a function of adapting sweep duration (t_s) in ms at 0.25 kHz (upper graph) and 1.0 kHz (lower graph). The adapting-stimulus repetition rate was 8/s and the value of F_m of the sinusoidal-F_m test-stimulus 8 Hz. Adapting ±ΔF was ±25 Hz at 0.25 kHz and ±80 Hz at 1.0 kHz. Vertical bars are ±1 standard deviation.


RBG 0·25 kHz
up
down
x2·0
x1·0
20
40
60
80
100
120
t_s (ms)
repetition rate = 8 /s


df / dt (Hzs^{-1})
3200
1600
1067
800
RBG 1·0 kHz
up
down
x 3
x2
x1
25
50
75
100

APPENDIX D: LATERAL INHIBITION IN HEARING

D.1 Physiological two-tone suppression

Two-tone inhibition or suppression (the latter term is favoured) is found in many species at the level of the cochlear nerve (Evans, 1975 for review) as well as higher levels (e.g. cochlear nucleus, Evans, 1975, inferior colliculus, Vartanian, 1974). The phenomenon involves the suppression of unit activity evoked by a tone or noise stimulus by another stimulus over a restricted range of frequencies and intensities (see Fig. D.1a). Suppression areas are asymmetrical and lie on either side of, sometimes overlapping, the excitatory area. The latencies of suppression effects are the same as those for excitation. The mechanism of the suppression effects is uncertain, though some evidence exists for lateral inhibition at the cochlear nucleus level but not the cochlear nerve level (Evans, 1975).

D.2 Psychophysical evidence for lateral suppression

Until recently direct psychophysical evidence for lateral suppression was lacking. Von Bekesy (1963) [J.Acoust.Soc.Am., 35, pp.588-601] found pitches corresponding to the upper and lower cut-off frequencies of an octave band of noise comparable to Mach bands in vision Ratliff, F (1965) [Mach Bands, Holden-Day] in the form of emphasis of the edges of the noise by contrast phenomena.

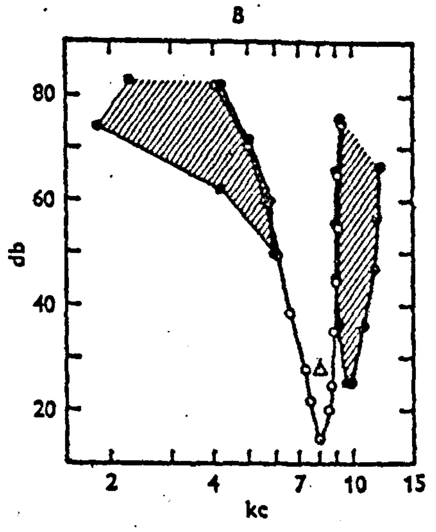
Houtgast (1972) found evidence for lateral suppression in the form of Mach band type phenomena using non-simultaneous masking techniques including the pulsation threshold technique as well as forward masking. Suppression effects took the form of marked edge effects in the masking pattern (Fig. D.1b). Houtgast (1972) also demonstrated a psychophysical phenomenon analogous to physiological two-tone suppression. This took the

Figure D.1: (a) Single cochlear fibre response are as for single tone excitation (open circles) and response areas of tones suppressing response to continuous tone at the frequency and intensity indicated by the triangle (hatched area and filled circles). From Arthur et al. (1971) [J.Physiol., 212, pp.593-609]

(b) Examples of edge effects in non-simultaneous masking conditions. From Houtgast (1972).

(c) Forward-masking patterns and unmasking (suppression) areas. From Shannon (1976).

a



b

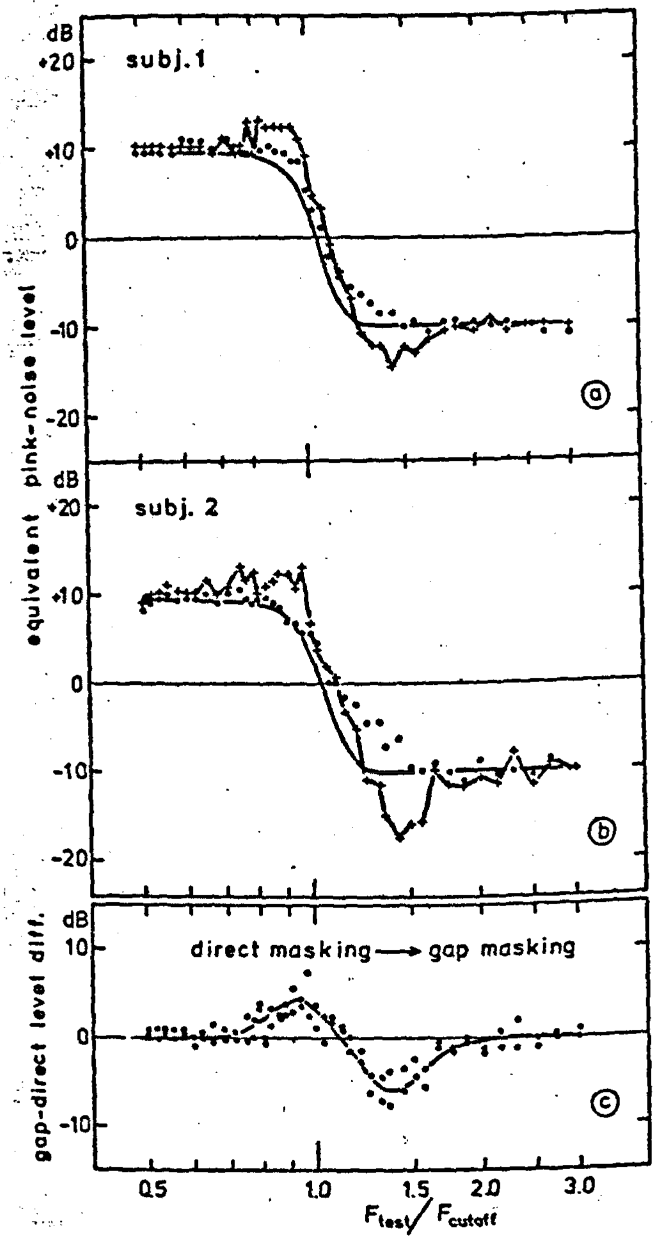


FIG. 3. Results obtained with the low-pass shaped masker. The variable is the cutoff frequency of the low-pass filter. Parts (a) and (b) represent the level of a pink-noise stimulus which is equivalent to the shaped stimulus with respect to (1) repeated-gap masking of a 1500-Hz test tone, (2) direct masking of a 1500-Hz test tone, and (3) output level of a narrow-bandpass filter centered at 1500 Hz. Part (c) presents the difference between the equivalent pink-noise levels based on repeated-gap masking and on direct masking. (+—+): gap masking; (···): direct masking; (——): physical.

C

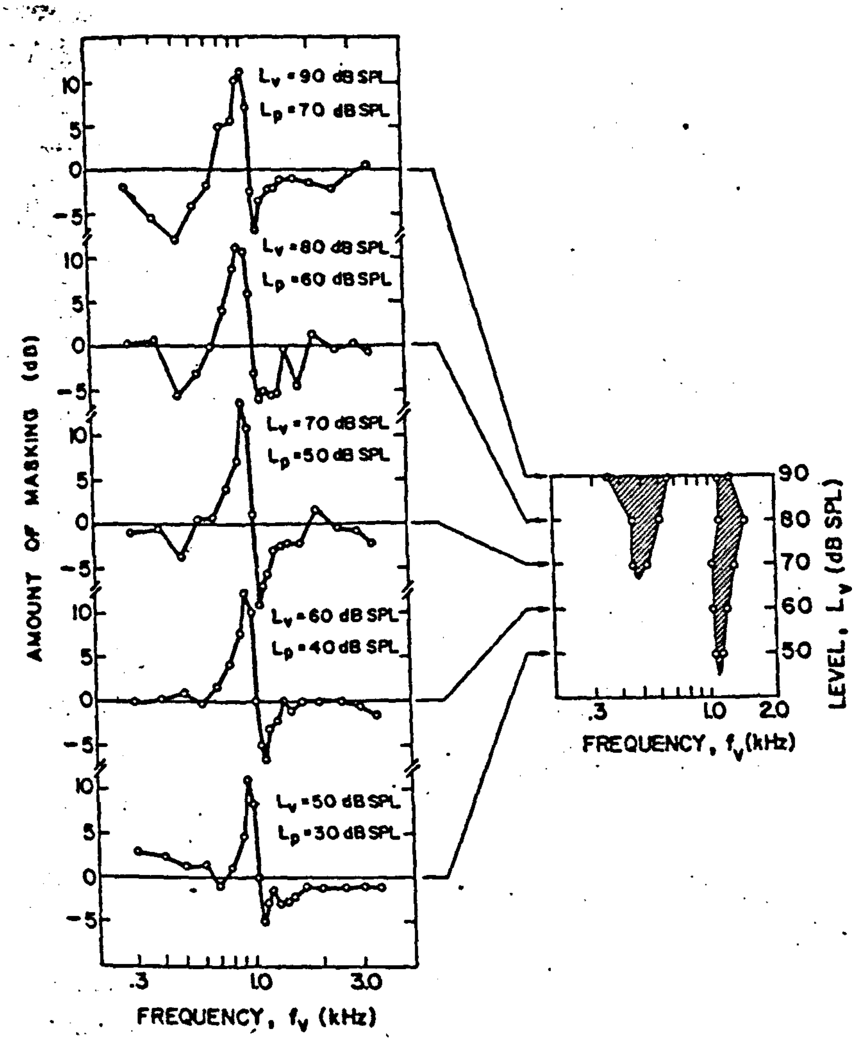


FIG. 6. Forward-masking patterns as a function of the overall masker level. The difference between the levels of the two masker components was fixed at 20 dB. The hatched areas in the composite figure indicate the values of f_v, L_v, and L_p ($L_p = L_v - 20$ dB) for which more than 3 dB of unmasking was observed (subjects SK, PP, and RS, $\tau = 0$ msec, $T = 20$ msec).

form of an unmasking effect produced by a second "suppressing" stimulus presented during the masker interval. Thus the masking of the probe stimulus is reduced by the suppressing stimulus. Suppression effects have been confirmed by Shannon (1976) and Terry and Moore (1977). Whereas the masker and probe (test) stimuli have the same frequency the suppressing stimulus is at a different frequency and intensity with respect to the masker allowing suppression areas to be mapped (see Fig. D.1c). Suppression areas are similar to those found in physiological two-tone suppression. Once again these effects are only observable with a non-simultaneous masking paradigm. More recently, Houtgast (1977) has produced further evidence for lateral suppression from measures of auditory frequency selectivity with rippled-noise maskers. In non-simultaneous stimulus conditions, bandwidths of half those obtained from simultaneous masking conditions are found.