DIRECTIONAL ADAPTATION TO FORMANT-LIKE FREQUENCY SWEEPS

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1. INTRODUCTION.

Physiological experiments have demonstrated neurones in various parts of the brain responsive to specific types of stimulus modulation [1-3]. Attempts to replicate these findings by psychophysical techniques in humans have led to the concept of feature specific channels [4-11]. The nature of this specificity is that exposure to one type of modulation, e.g. FM, raises the subsequent threshold for this type of modulation (by a factor of 2 or 3) but not for other types of modulation. Kay & Matthews [4] were able to show that this adaptation effect was specific to the carrier frequency region used and to the modulation rate. Gardner & Wilson [8] showed that the FM adaptation was directionally specific so that upsweep adaptors raised the threshold for upsweeps but not for downsweeps, and vice versa. Tansley & Regan [9] confirm this and also found that intensity upsweeps and downsweeps did likewise. In 1981 Diehl [12] cast doubts on the selective channel hypothesis for speech signals. Supporting these doubts, Wakefield & Viemeister [13] repeated the experiment of Gardner & Wilson [8] showing that the adaption factor of 1.7 represented only a small performance drop from 75% to 65%, and that this might be explained by cognitive factors which affect the subject's view of the reference signal. Moody et al [14] also questioned the selective channel hypothesis by showing that with repeated testing, the difference between adapted and unadapted thresholds gradually disappeared. They thought it possible, however, that their subjects learned to use another cue that was unaffected by adaptation. Their use of feedback of results would enhance this possibility. No other study has found this decrement of adaptation even though some experiments have lasted appreciably longer.

One of the shortcomings of the unidirectional sweep experiments is that the nature of threshold determination is such that the rate of change of frequency of the test stimulus can be very different from that of the adaptor, which may be inappropriate for the channel hypothesis. In view of these various difficulties and of the relevance of such studies to the recognition of speech signals, it was decided to investigate directional adaptation using a different type of stimulus and a different type of threshold determination. The stimuli were to be multiple-peaked noise signals somewhat akin to multiple-format speech signals and the thresholds were to be obtained (again using a forced-choice technique to minimise non-sensory factors) by reducing spectral peak-to-valley ratios rather than by altering the rates of change of frequency.

2. METHODS

2.1. Stimulus Generation

The frequency-sweeping adaptation and test stimuli were derived from two identical pseudorandom-sequence noise generators set to a relative delay, T, of 1 ms. Addition of such signals gives a comb-filtered noise with a power density spectrum of $A^2(1+\cos 2\pi fT)$. Therefore, for T = 1 ms, the peaks are spaced at 1 kHz intervals and have half-power bandwidths of 500 Hz. In order to cause continuous upwards or downwards motion of the peaks, the phases of all the components of one of the signals have to be set in rotation by a low-frequency modulating signal before addition to the other signal. This is achieved by passing the signal through two phase-shifting networks (ø andø+90°) which produce outputs differing by 90°±1° over the whole audible range. These outputs are multiplied by the in-phase and quadrature outputs from a low-frequency oscillator (see Fig. 1). The sum and

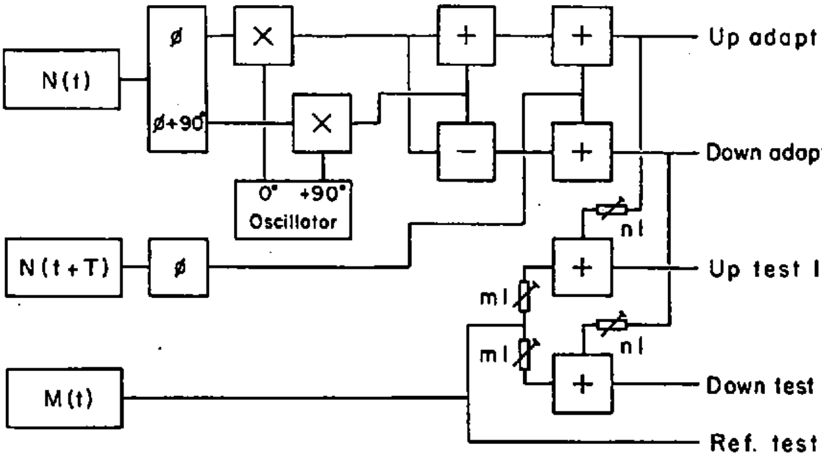


Fig. 1. Stimulus generation system, N(t) and N(t+T) are two pseudorandom noise generators with a relative delay, T=1ms, and M(t) is an analogue noise generator, ø and ø+90° are all-pass networks with a relative phase difference of 90°±1° from 4 Hz to 80 kHz. X,+,- represent analogue multipliers, adders and a subtractor, respectively. The quadrature oscillator was set at 3 Hz for one subject and 8 Hz for the others.

difference between these products represent signals whose phases are rotating clockwise and anti-clockwise, respectively, at the rate of the modulating signal, but which still have flat spectra and sound identical to the original pseudorandom sequence. A similar arbitrary phase function, ø, is applied to the delayed signal before adding it to the rotating vector signals. These final additions give the high peak-valley-ratio (PVR) upward and downward sweeping spectra used as adapting stimuli.

To produce the lower PVR signals required for the test signals an independent analogue noise, M(t), is added to reduce the contrast. The attenuation factors, mI and nI are set to give the required PVR and also to ensure that all the signals used have the same mean spectral density. Fig. 2 shows a representation of a downward sweeping test stimulus with a PVR of 1.7 (2.3 dB).

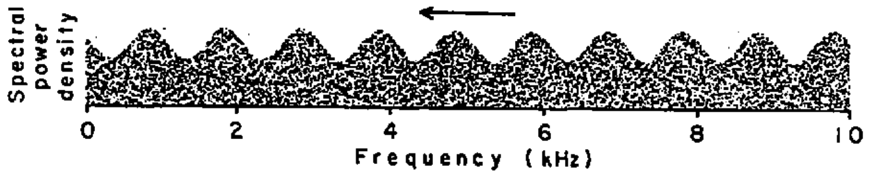


Fig. 2. A representation of the stimulus spectrum for a PVR of 1.7 (2.3 dB). The arrow is intended to indicate that all the ripples are moving downward in frequency. The adapting stimulus has a PVR > 30 dB.

2.2. Psychophysical Method.

A two-interval forced-choice (2-IFC) technique is used to determine the ear's sensitivity to sweeping spectral peaks. To obtain the threshold a series of stimulus pairs (1 and 2) is presented, one containing the target stimulus and the other a neutral reference signal of white noise. Indicator lights define the intervals for the subject and prompt him to respond by pressing a key to indicate in which interval the target stimulus occurred. The target stimulus is presented at one of four possible PVRs in order to bracket threshold, preferably between the two lowest levels. As the subject's response is recorded, randomisers reset the sequence of the stimulus-pair, the PVR level, and restart the stimulus sequence. Each threshold determination consists of about 100 stimulus pairs and the percentage correct at each level is plotted on probit paper. Threshold is taken as the interpolated stimulus value that would give a 75% correct response.

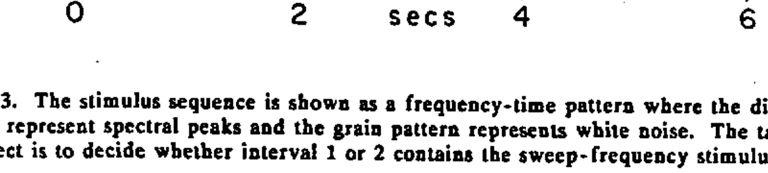


Fig. 3. The stimulus sequence is shown as a frequency-time pattern where the diagonal lines represent spectral peaks and the grain pattern represents white noise. The task of the subject is to decide whether interval 1 or 2 contains the sweep-frequency stimulus.

2.3. Experimental Procedure.
Stimuli were presented diotically via Sennheiser HD414 phones in a sound attenuating enclosure. The overall level of the stimuli was set to 50 dB above absolute threshold for each subject. The experimental stimulus sequence is illustrated in Fig. 3 for a downward sweeping adapting stimulus and an upward sweeping test stimulus in interval 2. The diagonal lines represent the frequency-time paths for the spectral peaks at 8 Hz modulating frequency, producing a temporal pattern of 8 peaks per second, or a spectral velocity of 8 kHz per second. The overall bandwidth, however, was not restricted to 10 kHz. The test stimulus durations and intervening intervals were all 0.25s and the adapting stimuli lasted for 5s. All combinations of upward and downward test and adapting stimuli were used. As the stimuli were all noise signals, rectangular gating functions were used. Starting phases of the adapting and test stimuli were random. Two subjects, JPW and EJC, used 8 Hz modulation rate whereas the other, NC, used 3 Hz. For JPW the tests were done alternately in the order shown and then in reverse order but for the other subjects a random sequence was used. All subjects had normal hearing threshold.

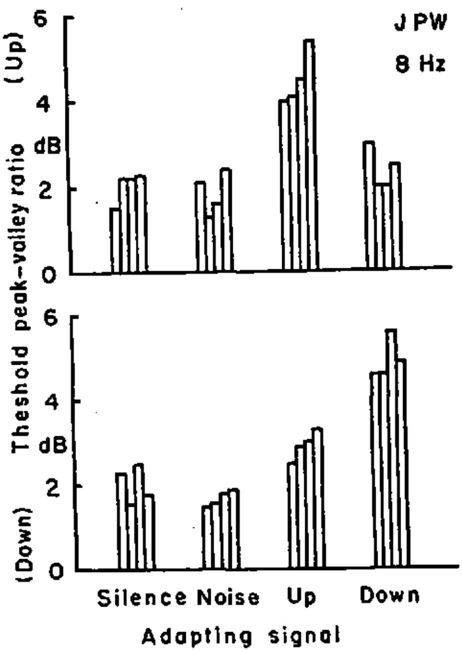
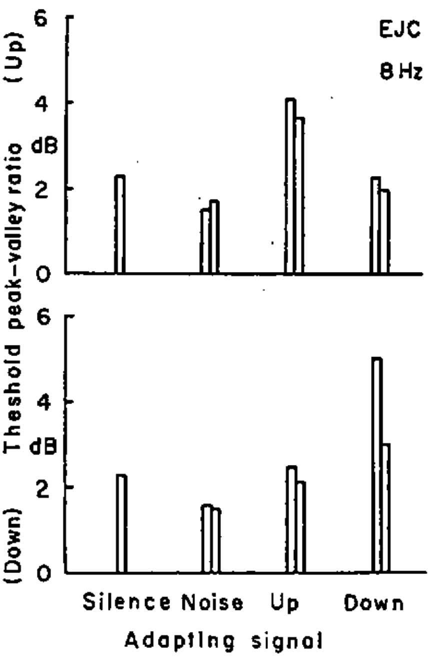


Fig. 4. Threshold PVR is plotted for upsweep test stimuli (above) and downsweeps (below) for a preceding stimulus of 2s silence, or 5s white noise, upward or downward, high-PVR stimuli. Subject JPW at 8 peaks per second.

DIRECTIONAL ADAPTATION TO FORMANT-LIKE FREQUENCY SWEEPS



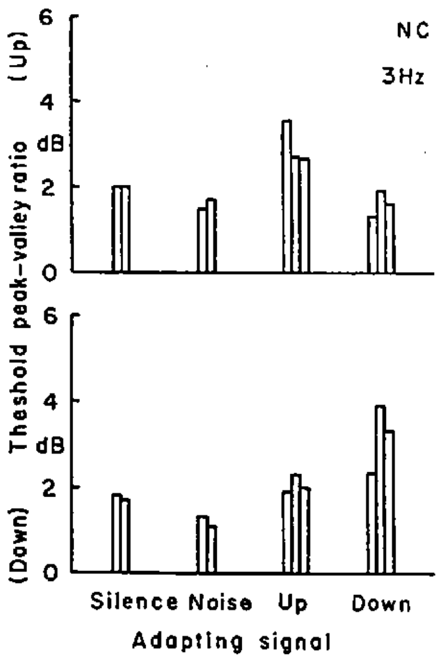


Fig. 5. As Fig. 4 for subject EJC at 8 peaks per second.

Fig. 6. As Fig. 4 for subject NC at 3 peaks per second.

3. RESULTS

The results are shown in Figs. 4,5 and 6. The most striking observation, which is statistically highly significant in most cases, is that in every case the highest threshold is obtained in response to a similar adapting stimulus. In other words an upsweep adaptor makes an upsweep test stimulus more difficult to detect but has little influence on a downsweep test stimulus, and a downsweep adaptor raises the threshold for a downsweep test but not for an upsweep test.

Some less striking tendencies can also be observed. The white noise adaptor in each case appears to reduce threshold slightly. There may also be a slight elevation for opposite sweeps. It should also be noted that there is no consistent difference between upward and downward thresholds in either the adapting or non-adapting cases.

DIRECTIONAL ADAPTATION TO FORMANT-LIKE FREQUENCY SWEEPS

4. DISCUSSION

These results demonstrate that broadband stimuli are capable of producing directional adaptation. Although the results are not quite so marked as for the earlier pure tone sweeps [8] the present stimulus parameters (1 kHz peak spacing and 8 or 3 Hz peak rate) are not necessarily optimal. In particular the broad bandwidth of the peaks (500 Hz) was chosen to form a distinct contrast with the tonal stimuli used previously and to ensure very adequate spectral resolution by the auditory filters in the mid-frequency range. Specifically the critical band is 500 Hz wide at 3 kHz and becomes 1 kHz wide at 5 kHz [15]. Therefore if frequency-sweep detection depends on frequency resolution one would expect a good response up to the 3 kHz part of the stimulus but little or no effect from 5 kHz upwards.

At the low frequency end, speech studies and the broad bandwidth used would imply that frequencies below 300 Hz are also going to contribute little to the response.

The modulation rate of 8 Hz was chosen because this rate had been used extensively in the tonal studies. In the present experiment (T = 1ms) this gives a constant rate of 8 kHz/s which in octave terms represents rates ranging from 3.8 oct./s at 3 kHz to 38 oct./s at 300 Hz. For comparison, studies of speech spectra and sweep-frequency sensitive neurones in animals both indicate that rates of change of 1 to 5 oct./s are most prominent [1-3]. This would imply that in the present case the dominant region would be at 2-3 kHz. To extend this downwards one can either increase the time delay or reduce the modulating frequency. The latter course was adopted for the third subject (NC) where 3 Hz was used. Unfortunately, if anything, this led to a reduced adaptation.

Concerning the criticism that adaptation decreases with repeated testing [14] it should be noted that no support for this hypothesis was found anywhere in this study. Although the overall sequence of experimental determinations was randomised, the results plotted in Figs. 4,5, and 6 are presented in the order performed for any specific condition. There is no tendency for these to become lower towards the right. Although these experiments were not as protracted as those of Moody et al [14] they did exceed the range over which most of their decrement occurred.

The other criticism that "adaptation" may represent a change of criterion rather than sensory changes [13] is also difficult to sustain. In our case, although the stimulus changes required were comparable, at a factor of about 2, the changes in subject performance were much greater than the change from 75% to 65% (a d′ difference of 0.41) reported by Wakefield and Viemeister [13]. The slopes of the psychometric functions were consistent throughout at about 10% (70 to 80%) per 0.4 dB for the control and non-adapting conditions and 10% per 0.8 dB for the adapting conditions. This would represent a decrement from 87 to 63% (a d′ difference of 1.1).

There is one further observation that might be made with regard to both these results and earlier ones. A frequent concomitant to adaptation is a negative after-image. This implies that we might have expected a facilitation following opposite stimulation. This was never found and the present results, if anything, show a slight adapting effect of opposite stimulation.

In conclusion, the present results conform with the majority of previous findings in implicating selective channel adaptation. They extend the results to unidirectional broadband stimuli and conditions where the adaptation is measured by changes in broadband masker levels rather by frequency excursion.

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