Facilitation of intensity discrimination of short stimuli in noise occurs not far from a stimuli detection threshold

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Adaptation is one of the important properties of any sensory receptors. Auditory adaptation is based on properties of peripheral receptors and central neurons. There are some questions. What is the auditory adaptation mechanism for short high frequency stimuli like? How does the auditory system keep track of amplitude changes of stimuli? The answer is: stimuli might be mixed with noise of different origins. Noise can adapt auditory system and can help to discrimination of stimuli. The simulation researches of peripheral encoding have shown that the amplitude temporal structure of short stimulus acting in silence or in noise can be preserved. It occurs when intensity of stimuli is up to fibers detection thresholds. For each stimulus level there is the certain noise level, when amplitude structure can be detected without any losses. The validity of these statements has been tested in auditory experiments. Intensity discrimination (ID) thresholds have been estimated for short stimuli presented in silence or for short stimuli under simultaneous and forward masking by noise. In a range of average stimulus intensity and for each stimulus level there is the certain noise level when ID is better in noise than in silence. The ID facilitation is registered close to stimulus detection thresholds and after adaptation of hearing by noise. The results for the auditory and the simulation experiments were similar.

1 Introduction

Adaptation is one of the important properties of any sensory receptor. The beginning of intense and long duration stimulus is accompanied by appearing of the onset response or the synchronous reaction of the group of auditory nerve fibers (ANF) with high level of firing rate. Due to adaptation the firing rate is down in each fiber while reaction of the ANF-group response is desynchronizing. The onset response disappears. Adaptation leads to decrease of the fibers activity and get ready the ANF-group for the next onset response even at the lowest amplitude stimuli changes. Nevertheless the auditory system can analyze the stimuli with duration that is less than duration of adaptation processes. What is the auditory adaptation mechanism for short high frequency stimuli like? How does the auditory system desynchronize the onset response? How does adaptation influence on structure of short volley of ANF, encoded stimuli? How does the auditory system keep track of the amplitude changes of stimuli? It is assumed that stimuli are mixed with noise of different origins. External noises desynchronize the onset response of ANF-group and provide a peripheral amplitude temporal analysis of the stimuli.

It is important to note the essential properties of peripheral signal transformation for the adaptation mechanism. At the first, there is an active mechanism of outer hair cells (OHC). It helps to preserve a phase- synchronized reaction with the stimuli in inner hair cells (IHC) [1]. At the second, there is the divergence of an excitement of one IHC to the ANF-group and the principle of volley was declared [2]. At the third, there is a basilar-membrane (BM) nonlinearity that is also related with the active mechanism of OHC [3]. It is detected as smooth growing of the BM displacements in the range of average stimuli intensities. The BM nonlinearity prohibits growing of amplitude of round-window potentials [4], and, as it can be assumed, a number of excited ANF.

Because of ANF fixed number and ANF recovery properties the realization of the principle of volley has distinctive features for short stimuli. These features have been revealed in the result of the simulation and the psychoacoustics experiments for stimuli under simultaneous masking [4-7, 10-12]. In given work the hypothesis of participation of external noises in auditory adaptation to short stimuli under forward masking is tested. This testing will be done thought comparison of our simulation and psychoacoustic data, as well data from works [8, 9].

2 The simulation researchers

The principle of volleys is based on reactions of two types in ANF-group: "stochastic" and "deterministic". The stochastic reactions are caused by a spontaneous activity (SA) of ANF. The deterministic reactions are determined by duration, frequency, level of stimulus and so the ANF recovery processes influence them. It is possible to use the modified double pulse’s method for a separate estimation of contribution of stochastic and deterministic reactions in the response of ANF-group [5].

The double pulse's method is usually used for estimation of neuron’ recovery processes (refractoriness and adaptation) [13]. The recovery process is indicated as the dependence of relative amplitudes of the second-pulse response or P2/P1 on inter-pulse intervals t, where P1 and P2 are sums of spikes, arisen by the first and second pulses. If pulses are enough short, the contributions of the reactions of two types (Ps2 and Pd2) in the reaction, evoked by the second pulse, can be estimated. They are calculated from P2-response, given that the second-pulse response occurs under condition of absence or occurrence of the first-pulse response, respectively. Note, P2=Ps2+Pd2, where Ps2 and Pd2 are the stochastic and deterministic component in P2-response.

It has been detected [5] that short volley of ANF-group can reproduce the double pulses structure without any losses only under conditions when the stimulus is showed in isolation or in simultaneous noise and when the stimuli intensity approaches detection threshold of ANF-group. There is the certain noise level for each stimuli level, when this rule is right. Reproduction of the structure is promoted by stochastic reactions whose contribution is maximal near detection threshold. The deterministic reactions, whose contribution is maximal at the high stimuli levels, destroy an ability of ANF-group reproducing the structure.

Changes of the stimuli or noise levels are accompanied by mutual redistribution of stochastic and deterministic reactions in P2-response. If ANF-group has high SA, the redistribution is smooth. If ANF-group has low SA, there is a gap between the stochastic and deterministic reactions. The reproduction of the double pulse structure at this gap can be worsening in noise [5]. In this work a realization of the principle of volleys will be shown for the stimuli under forward masking by noise.

2.1 The model of auditory nerve fiber

A phenomenological ANF model has been developed earlier [14]. It transforms short stimulus to sequences of action potentials (spikes), taking into account properties of SA, refractoriness and adaptation.

The ANF model performs the following transformations of the input signal X(t): (1) band-pass filtration (the central frequency of the filter sets the characteristic frequency (CF) of a fibre); (2) compression and detecting of a signal; (3) forming of synaptic noises and SA; (4) low frequency filtration of a synaptic noise with a time constant equal 0,2 ms; (5) transformation of synaptic potentials G(t) in sequence of spikes ΣPi by comparison G(t) with threshold H(t); (6) change in time of H(t) after spikes generation. Properties of the threshold function H(t) assign the refractoriness and adaptation properties.

Parameters of the model were chosen so that the models reproduced known relationship of the ANF physiological properties with different SA. The more SA, (1) the less detection thresholds of fibre; (2) the more steepness of dependence of average firing rate on stimuli level; (3) the worse such fibre reproduces an envelope of amplitude-modulated signal; and (4) the less adaptation property according of work [15].

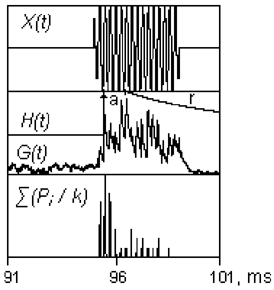

Fig.1 Model synaptic potential G(t), threshold function H(t) and histogram ∑(Pi/k) of ANF-group containing 100-fibre models, arisen on pulse X(t). On abscise: time in ms, on ordinate: amplitudes. Arrow marks a moment of spike's generation, "a" and "r" mark absolute and relative refractoriness.

Reactions of different model stages evoked by short stimuli are shown on fig.1. A stimulus was a tone burst with frequency of 4 kHz and duration of 4 ms. All CF of ANF models in group were 4 kHz. The total reaction of ANF-group was represented as histogram. Temporal step of calculation was equal 1 mksec. Temporal step of histogram calculation (bin) was 10 mksec. Synaptic potential has casual fluctuations. The end of histogram is less than its beginning due to fibre recovery properties.

A temporal window of the histogram divided into two parts with duration of 2 ms. P1- and P2- responses have been received in the first and the second parts of the window. Relative P2/P1-, Ps2/P1- and Pd2/P1- responses were also calculated. If P2/P1-response comes close to 1, the stimulus structure is reproduced.

2.2 The results of simulation experiments

In all case stimuli was presented under forward masking. Masker was broadband noise with 4 kHz spectrum maximum. The noise durations was 80 ms, stimulus began in 5 ms after noise. The responses of fiber models with low SA are shown on fig. 2. Changing of noise level can either make worse or improve reproduction of the stimulus structure (fig. 2, I).

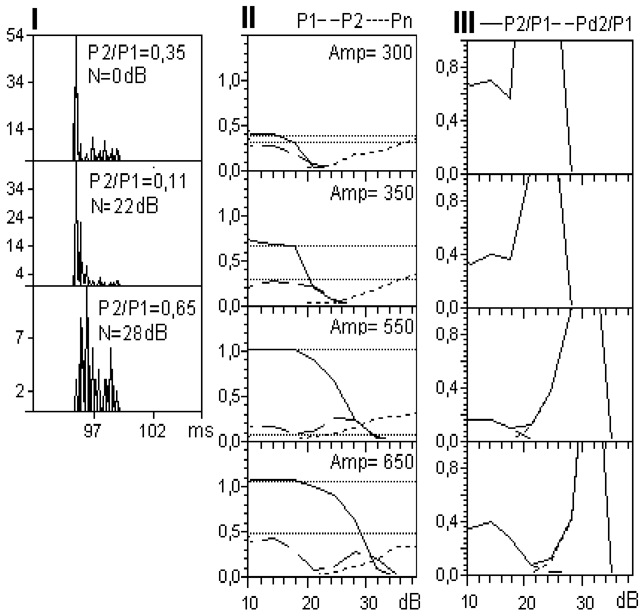

Fig.2. Reactions of ANF-group caused by stimulus under forward masking. (I): Histograms, received on the stimulus with amplitude of 650. Parameters are P2/P1-response and noise level. On abscise: time in ms; on ordinate: sum of spikes, arisen in ANF-group containing 100 fibers. (II, III): Dependences of P1-, P2-, Pn- and P2/P1-, Ps2/P1-, Pd2/P1-responses on noise level. Parameters are the stimulus amplitudes. On abscise: noise level in dB (0 dB is accepted for noise detection threshold in fibers with high SA); on ordinate: amplitudes of responses. Dot lines correspond to P1- and P2- responses, received in silence. Pn- response is reaction of ANF-group on noise, estimated in a window of 2 ms not far from the end of noise.

Dependence of P1- and P2- and also P2/P1-, Ps2/P1-Pd2/P1- responses on noise level, received at the different stimuli amplitudes, are shown on fig.2, II, III.

The general rules of reproduction of the stimulus structure under simultaneous masking [5, 12] are kept for stimulus under forward masking. Namely: (1) If noise is absent and the stimulus level is close to detection thresholds of ANF-group, the stimulus structure is almost reproduced. P1/P2-response is close to 1 (see responses at Amp=300, N=10 dB). (2) The growth of the stimulus level (noise is absent) conducts at first to distortion of the stimulus structure, P1 > P2 (Amp=350, N=10 dB), and then to occurrence of the deterministic reaction or Pd2/P1-response (Amp=550, N=10 dB). (3) When the ANF-group response on noise (Pn-response) is appeared, P1- and P2- responses decrease. (4) If stimulus is close to detection threshold then (a) absolute sensitivity to the stimulus decreases; (b) stochastic reaction or Ps2/P1-response appears; (c) P2/P1-response and differential sensitivity to the stimulus structure grow. (5) Greater stimulus level requires greater noise level for full masking. For instance, the noise of 24 dB masks the stimulus with amplitude of 300, and the noise of 34 dB masks the stimulus with amplitude of 650.

It is necessary to note a feature of the structure reproduction, exhibited only in the reactions of fibers with low SA. This is a deterioration of the structure reproduction in noise. The feature is revealed easily under forward masking, but it is more difficult to detect it under simultaneous masking.

If noise is absent the stochastic reaction predominates in P1- and P2- responses. Both P1- and P2- responses are small, but identical at the smallest stimulus levels (fig. 2, II, III, N=10 dB; Amp=300). The growth of stimulus level is accompanied by increasing of P1-response, leaving constant or reducing of P2-response (fig. 2, II, III, N=10 dB; Amp=350 and Amp=550). After reduction of P2-response up to zero and after involving virtually all fibers in P1-response, the synchronous onset response is appeared (fig. 2, II, III, N=10 dB; Amp=550). The further growth of stimulus level is accompanied by occurrence of the deterministic reaction, because the P2-response grows again (fig. 2, II, III, N=10 dB; Amp=650).

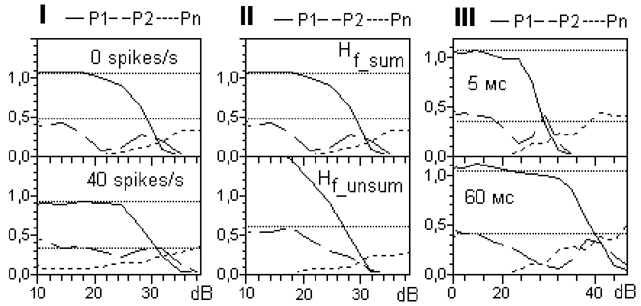

Fig.3. Dependences of P1- and P2- responses on noise level in dB, received at different fluctuation levels of synaptic potentials caused SA (SA is specified as parameter) (I); at different adaptation properties (II); at different delays between stimulus and noise (the delay is specified as parameter) (III). The stimulus amplitude is equal 650. Other indications see on fig. 2.

Addition of external noise triggers the same process in the reverse order (fig. 2, II, III, Amp=650). At first the noise has reduced P2-response or the deterministic reactions up to zero (N=22 dB) but the stochastic reactions has not been appeared yet. It is expressed as gap between these reactions. The further increasing of the noise level makes P1-response reduce and P2-response increase. P1- response becomes identical to P2-response at noise levels of 28-32 dB. The next growth of noise level up to 36 dB reduces both responses up to zero. Such gap is not present in fibers with a high fluctuations of synaptic potentials (fig. 3, I) or in fibers with poor adaptation properties (fig. 3, II). Note increasing of delay leads gap between deterministic and stochastic reactions to increase (fig. 3, III). Simultaneously a range of the noise levels where the stimulus structure is reproduced becomes wider.

The simulation researches have shown: (1) The stimuli structure is reproduced in reaction of ANF-group without any losses when the stimuli level is closed to detection threshold, regardless of the fact that the stimuli are acting in silence or in noise. There is the certain noise level for each stimulus level, when the structure is reproduced. (2) "Strong" noise improves the structure reproduction; "average" noise worsens the ones. (3) Extension of the delay between stimulus and noise expands the range of the noise levels that the structure reproduction is observed in.

3 The psychoacoustic researchers

By present time it is known enough measurements, finding out the deterioration of intensity discrimination (ID) of short stimulus with average intensities in silence and the facilitation of ID of stimuli under simultaneous or forward masking [4, 6-11]. Comparing the results of these measurements with results of our simulation researches, we have found out some overall rules. They are assumed to be appeared because the structure and the intensity of short stimulus can be encoded on periphery by the fixed number of fibers. Therefore it has been solved to check up a hypothesis about participation of external noise in auditory adaptation for short stimulus in psychoacoustic measurements that are being similar to carried out ones [4, 6-11] and are taking into account the results of the simulation researches. It was estimated the intensity discrimination thresholds (IDT) in silence and in noise. As well under forward masking it have been measured dependences of masking level on noise level for comparison differential and absolute auditory sensitivity.

3.1 Stimuli and listeners

Stimuli were Gaussian-windowed tones with carrier frequency of 4 kHz. The bandwidth might be equal 5000, 1000, 200 and 40 Hz in the first experiment. It was equal 1000 Hz in other two ones. Stimuli were presented in silence (the first experiment) and in noise under simultaneous masking through 0,45 s after noise beginning (the second experiment) or under forward masking (the third experiment). The noise spectrum' maximum and its bandwidth were equal 4 kHz and 1000 Hz. The stimulus or noise levels of were estimated in dB sensation level (SL).

Four normal-hearing listeners were used. The experiment was controlled by an IBM PC-compatible computer. Listeners were tested individually in a soundproof camera. The stimuli were presented on both ears.

3.2 Method

Thresholds have been obtained using a two-interval forced-choice adaptive procedure with a decision rule that estimates 70.7% correct. Durations and a pause of test sequence were equal 0,7 s. Eleven turnpoints were obtained. The threshold was taken as the mean level across last eight turnpoints. At least three valid runs were obtained. The thresholds were calculated as the mean across three listeners.

3.3 Result and discussion

In the first series the IDT for stimuli with different bandwidths and levels were measured (fig. 4). It is well known [4, 6, 7] dependence of IDT on level in silence was non monotonous. So that IDT noticeably rose in the level range of 20-30 dB. The value of deterioration depends on the bandwidths. The worst thresholds were received for the bandwidths of 1000 and 200 Hz and for the level of 20 dB. IDT decreased if the bandwidth was expanded up to 5000 Hz or narrowed up to 40 Hz. The maximal value of IDT was displaced to the high stimulus level or to 30 dB at the bandwidth of 40 Hz. The bandwidths of 1000 and 200 Hz are equal to or less then the critical band. The stimulus durations are equal 1 and 5 ms, accordingly. It is quite probable, that a basis of IDT deterioration is short volley of the excited fibers encoding the amplitude–temporal, but not spectral structure of stimuli. It means the onset response arisen in the fixed number of fibers can worsen discrimination. The similar result and explanation we can meet in [11].

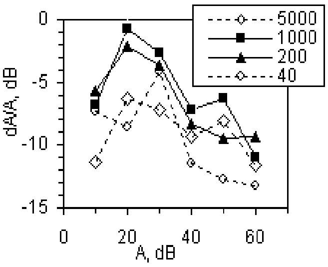

Fig.4. Dependence of IDT on level of the stimuli presented in silence. Parameters are the stimulus bandwidths in Hz. On abscise: the stimulus level or A in dB SL; on ordinate: IDT as dA/A in dB, where dA is the minimal increment of intensity found out by the listener.

The purpose of measurements in the second and third series was to define conditions of the ID facilitation in noise.

The second series repeated known measurements of IDT in noise [6], but in other conditions. It has been defined dependence of IDT on the noise level (fig. 5). The stimulus levels were different. The symbols on ordinate show IDT, received in silence. The symbols on abscise mark the noise levels when stimulus given level is not found out by the listener and a discrimination intensity task turns into a stimulus detection task.

If the stimulus level is equal 10 dB, the adding of noise worsens IDT. The ID facilitation appears for the stimuli with level of 20 dB. It decreases with growth of the level from 30 up to 50 dB and absolutely disappears at the level of 60 dB. The ID facilitation is more, than the stimulus level is closer to detection threshold of stimulus in noise. The least IDT for stimuli with the level of 20, 30 40 and 50 dB SL have been received at the noise levels of 22, 30, 40 and 46 dB SL, accordingly. It is possible to estimate a value of facilitation as a difference between IDT received in silence, and the minimal IDT in noise. The value has made 7 dB at the stimulus level of 20 dB; 4 dB at 30 dB; 5 dB at 40 dB and 2 dB at 50 dB. Thus, there is the certain noise level for stimulus level from range of 20-50 dB when IDT determined close to detection threshold is noticeably less in noise then in silence.

There is another effect. An additive adding of weak noise with stimulus of 30 and 40 dB can worsen IDT approximately to 3 dB in comparison with IDT received in silence. The same result has been received earlier in [10].

A basis of third series of measurements was experiments from known works [8, 9], but also the experiment conditions have been changed in according to the results of simulation researches. The dependences of masking level and IDT of stimulus of 20 dB on the noise level have been received. The masker was the same noise with duration of 0,1 and 0,6 s. The delays between the end of noise and the middle of the stimulus were 3, 12 and 60 ms.

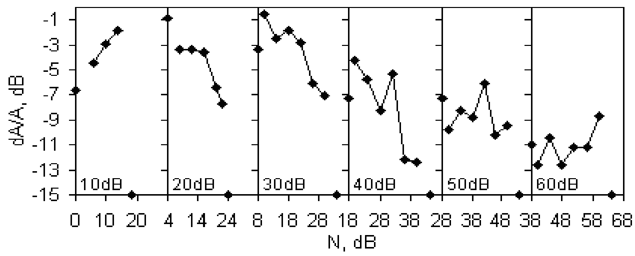

Fig.5. Dependences of IDT on noise level for the stimuli under simultaneous masking. Parameters are the stimulus levels in dB SL. On abscise: noise level in dB SL; on ordinate: IDT in dB, as on fig 4.

The masking threshold rather monotonously grows with growth of the noise level (fig. 6, top) and poorly depends on the noise duration. At that time IDT have non monotonic character and obviously depend on the noise duration and level (fig. 6, bottom). In all cases the smallest IDT have been received when the masking level was almost 10 dB.

The value of facilitation depends on the delay, level and duration of noise. With the parameters' increasing the ID facilitation grows. If the delays are 2 and 12 ms, the value might be equal 2 or 6 dB at the noise duration of 0,1 or 0,6 s (fig. 6, I, II). Increasing of the delay up to 60 ms conduce not only to increasing in the value up to 7 or 14 dB at noise duration of 0,1 s or 0,6 s, but also to broadening in the range of noise levels where this ID facilitation can be detected (fig. 6, III, bottom). Obviously a slight slope of the dependence of masking level on noise level is assisted these increasing and broadening (fig. 6, III, top). This fact has been predicted by simulation experiments.

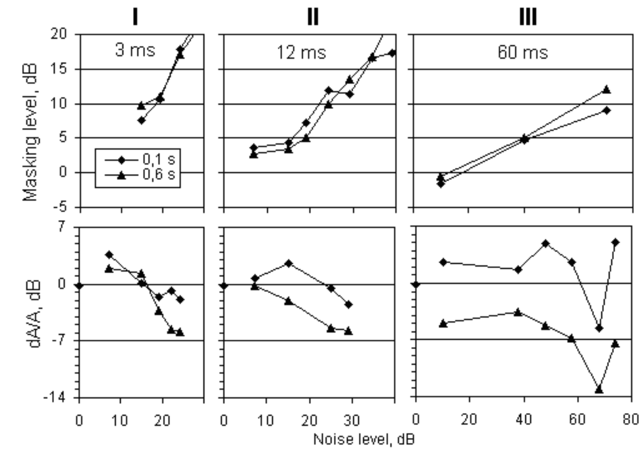

Fig. 6. Dependences of the masking levels (top) and IDT (bottom) on the noise level for the stimulus under forward masking. Parameters are the delays between stimulus and noise in ms and the noise durations in s. On abscise: noise level in dB. On ordinate: the masking level in dB; and IDT in dB, as on fig 4.

If delay is equal 0,1 s the region of the ID facilitation can be preceded the region of ID deterioration. At masking level of 5 dB the ID becomes worse in noise, than in silence. Perhaps, the same ID deterioration was found out earlier [8, 9]. The simulation researchers have shown that the onset response of ANF-group can be greater in noise then in silence due to redistribution of stochastic and deterministic reactions (fig. 2, II, III, Amp=650). There are different ways for de-synchronizing of the onset response. All of them have to increase contribution of stochastic reaction. One way is provided by the addition of simultaneous noises to the stimuli ([6, 9] and fig.5), the other by the increasing of the masking levels so that the stimuli level tend to detection threshold (fig. 6).

The ID deterioration practically is absent if noise duration is 0,6 s (fig. 6, II,III). Probably, the adaptation by a long-lasting noise does not accompany by the increasing of the onset response. According to the simulation experiment, it occurs when the gap between stochastic and deterministic reactions is removed by the changing in adaptation properties (fig. 3, II).

The psychoacoustic researches have shown: (1) the intensity discrimination of the stimuli with bandwidth limited by one critical band is better if the stimulus level is close to the detection-threshold, in spite of the of the fact that the stimuli are acting in silence or in noise. For stimuli under simultaneous masking in the range of stimuli average intensities there is a certain noise level for each stimulus level, when ID is better in noise, than in silence. (2) For stimuli under forward masking and the masker duration of 0,1 ms the "strong" noise (the masking level is 10 dB) is capable to improve ID, and the "average" noise (the masking level is 5 dB) to worsen ones. The ID is not worsened at noise duration of 0,6 ms. (3) For stimuli under forward masking the rising of either the masker duration or the delay between stimulus and noise increases the value of the ID facilitation and extends the range of the noise level where the facilitation have been observed. (4) The simulation experiments have been shown that all these facts can be explained by the redistribution of stochastic and deterministic reactions of invariable number of the excited auditory nerve fibers.

4 Conclusion

In the given work the hypothesis about participation of external noise in auditory adaptation to short stimulus was tested. We have found confirmation of it by coincidence of the results of the psychoacoustic and the simulation researches. External noise adapts auditory system and provides the ID facilitation. The most probably, this is the peripheral adaptation. We used short stimuli with bandwidth limited by one critical band. The number of excited fibers with similar characteristic frequencies encoding stimuli of average intensity is stayed permanent because of the BM nonlinearity and the onset response of such ANF-group can worsen the ID.

Presumably, the effect of the ID deterioration is absent when the number of spikes generated by the excited auditory nerve fibers varies proportionally with the stimuli intensity. I.e. short volley of fibers saves information about intensity for stimuli of low and high intensity presented in silence. The same happens for stimuli of average intensity presented in noise when their levels are close to detection threshold.

These features were assumed to be kept in similar form, while stimulus duration is less than duration of fibers recovery processes and bandwidth is less then the critical band.

Acknowledgments

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