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# CENTRAL PITCH AND AUDITORY LATERALIZATION

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## AIM

The sensation of pitch appears normally to arise from the operation of a multiplicity of mechanisms. It is not readily possible to distinguish their relative contributions and it would be an advantage to be able to study an effect which was dependent on the operation of only one type of mediation. The aim of the present experiments was to arrive at and to examine a situation in which only a neural mechanism contributed to the sensation.

Auditory lateralization can be made to depend only on the temporal difference between the stimuli applied to the two ears. When this condition is obtained the lateralization sensation is due only to the operation of a neural mechanism, since peripheral analysis cannot account for the effects observed. By examining the sensation of pitch which can be associated with this type of lateralization, it seems possible to arrange for a pitch sensation to be similarly independent of the action of peripheral analysis.

## LATERALIZATION AND PITCH

In the absence of peripheral clues such as amplitude or spectral difference between the two ears, lateralization can occur for a temporal difference which may be as low as 10μsec (Mills, 1958), or as high as 10 msec (Blodgett *et al.*, 1956). Although the point has not been explicitly investigated, the possibility of a physical, bone conduction, rather than a neural interaction being basic to these temporal lateralization phenomena is easy to exclude in informal listening and, because of the low sensation level (SL) at which the effects can occur, to dismiss experimentally. Fig. 1 outlines the basis of an experimental arrangement for which lateralization results only from the temporal difference, $\tau$ , in time of arrival at the two ears of otherwise identical stimuli. As $\tau$ is increased, the auditory image moves further to the left until the delay is of the order of 1 msec. Beyond this limit, which corresponds roughly to the time needed for airborne sound to cross a distance comparable to the width of the listener's head, there is little practical utility in being able to process time differences for the purposes of lateralization. This ability, however, persists.

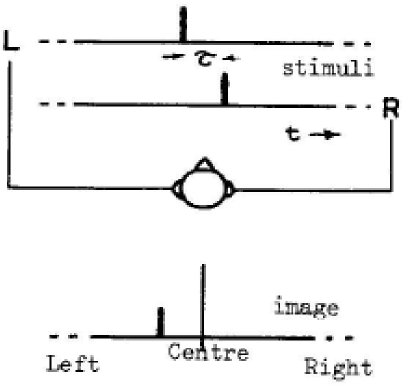


Fig. 1 Lateralization image representation for a left advanced click

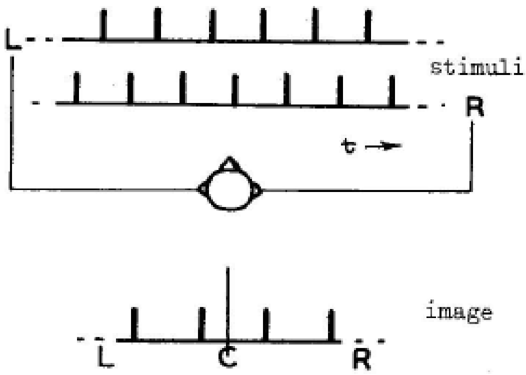


Fig. 2 Lateralization image representation for a left advanced click train

Since the mechanism exists for lateralizing a single click, the binaural presentation of a click train could result in an array of similar lateralization images. When this click train is periodic, as for the arrangement shown in Fig. 2, a sensation of pitch can be produced. This pitch is of course not dependent on the binaural nature of the presentation but in normal listening it would always be associated with the array's regular spacing. Two classes of array can be distinguished. The first is associated with an adjacent image spacing which could arise from two causes. Either from the lateralization of adjacent spatially separated independent acoustic sources or from the binaural response to a regular stimulus whose period is less than the maximum possible interaural delay. The second class of array can only be associated with the binaural response to a regular stimulus, one whose period is greater than the maximum possible interaural delay and less than about 10 msec.

Both of these classes of array could be basic to a central process of analysis akin to that postulated for the first in Licklider's Triplex Hypothesis (1962). The second class can have no lateralization function and if employed at all could only contribute to a process of signal analysis, one aspect of which, as a result of the array's regular spacing, might be related to the perception of pitch. This, however, is mere conjecture since an association between these arrays and pitch is as difficult to disentangle for ordinary stimuli as that between frequency and periodicity pitch. It would nevertheless be possible to test the principle, if a lateralization array could be set up using stimuli which were devoid of periodicity.

**SYNTHESIS OF A LATERALIZATION ARRAY**

The single lateralization image of Fig. 1 can be obtained for a click source or for noise with the delay line arrangement of Fig. 3. When noise is used the image is somewhat more diffuse but still well defined. The spectral envelope of the stimulus at each ear is entirely determined by the source, and on a long term basis can be completely free of peaks and troughs. The same technique can also be employed in order to build up a multiple image array. Fig. 4 shows how a three-lobe lateralization array can be constructed (the word "lobe" is employed here to denote the physical correlate of a possible subjective lateralization image). The use of a separate noise source for each lobe of the array, as for Fig. 3, produces an acoustic stimulus which has a smooth spectral envelope and a pressure-time waveform quite devoid of the periodic peaks which would ordinarily accompany a structured lateralization array of this type.

If, as in Fig. 4, the delays employed are of equal value, the pattern corresponds to the three central images that one might expect to get from an in-phase binaural periodic pulse train stimulation. Maximum congruence occurs for the delay, τ equal to the pulse train period.

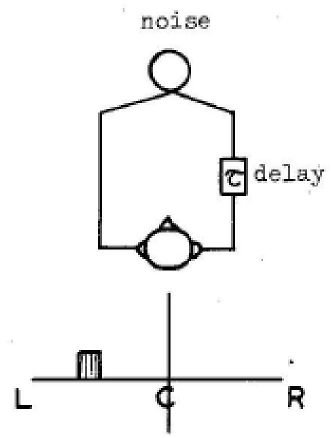


Fig. 3. Single lateralization lobe.

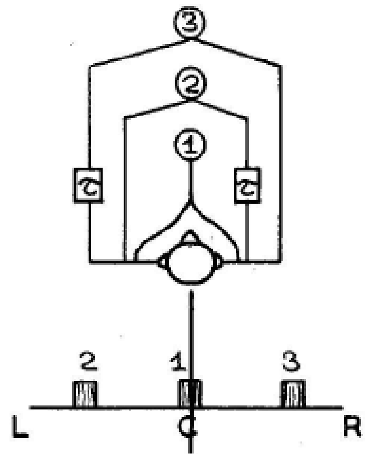


Fig. 4. Three lateralization lobes from three independent sources

**FREE-SPACE EXPERIMENT**

A particularly simple way of producing the single lobe of Fig. 3 is shown in Fig. Sa where the sound source and the subject are in an anechoic room. For small $\theta$, small interaural delays are obtained but $\theta = \pi/2$ gives only a moderate delay, corresponding to the head width. This disadvantage is partly overcome with the arrangement of Fig. 5b by using microphones which separately drive sound excluding earphones and which are set on a head arm at a distance from each other. The use of an additional independent sound source makes it possible to form two lobes, 2 and 3 of Fig. 4.

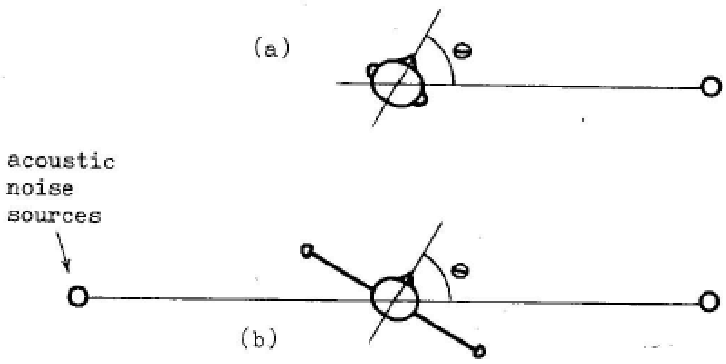


Fig. 5. (a) variable single lobe with small $\tau$ range;
(b) variable double lobe with moderate $\tau$ range

This experimental arrangement, Fig. 5b, was set up in a large anechoic room (10 m high and 14 x9 $m^2$) with a maximum horizontal diagonal spacing between the sound sources. The maximum. interaural delay, $\tau$, was 2 msec, using a symmetrically supported microphone arm and microphones of uniform polar response. With both sound sources operating there was a distinct pitch in the noise which varied with $\theta$. As $\theta$ approached zero from $\pi/2$, the pitch at first increased and then disappeared as the subject's head turned to face the source. The process was repeated cyclically for the other three quadrants with the pitch being at a minimum for $\theta = \pm\pi/2$. It was not possible to hear this pitch if attention was directed to lateralization. With only one sound source operating, rotation of the head merely produced a slight diffuse change in the auditory quality of the stimulus as the lobe was displaced from the centre. With both sound sources but only one microphone operating, both pitch and lateralization disappeared leaving a uniform auditory sensation which was independent of rotation. It is worth noting that the pitch was most clearly heard when the head was actually turning, and that the pitch lagged on $\theta$. Even for large $\tau$ the sensation of pitch was centrally located.

**DELAY-LINE EXPERIMENT**

The two most important results of the free-space experiment are that: (1) it is possible to derive a sensation of pitch from, stimulus configurations capable of producing a lateralization, (2) the lateralization must have at least two lobes.

Another, simpler, way of providing two lobes is by removing noise source 3 from the arrangement of Fig. 4. This leaves an array of the type shown in Fig. 6a, which requires only one continuously variable delay line, and in-phase stimulation.

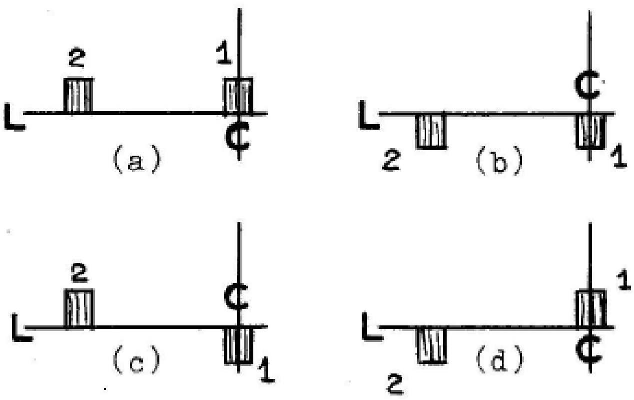


Fig. 6. Two lobe lateralization arrays with in-phase (a) & (b) and opposite-phase (c) & (d) lobe stimulus connections

This was set up using 3 kHz low-pass clipped noise, a forty section shift register delay line, with a stepping rate continuously variable between 10 kHz and 100 kHz, circumaural headphones independently fed from 2 kHz low-pass filters and an SL of 25 dB. The stimuli for this lateralization pattern can also give rise to a sensation of pitch having the same characteristics as for Fig. 5b; and, as before, if one lateralization lobe is removed, in whatever fashion, the pitch disappears. It is important that, given the left lateralization, the pitch is produced by the addition of what would normally be regarded as in-phase masking noise to the two ears from another source.

The reversal of the connections to either headphone reverses the polarity of both lobes and this is represented in Fig. 6b. If the phase of noise source 1 is reversed at only one ear, Fig. 6c represents the lobe pattern and if a stimulus from noise source 2 is reversed at one ear the pattern of Fig. 6d results. All four of these configurations give rise to a sensation of pitch, and, in every case, if one of the four stimulus connections to the earphones is removed, the pitch sensation is completely eliminated. Not all listeners are sensitive to the pitch (although all players of stringed instruments respond) but most can hear it and the same characteristics apply as for the free-space experiment. It is, however, more noticeable with this arrangement that the pitch follows rapid changes of delay fairly slowly. Lateralization and pitch do not exist together and even for the lowest pitch the sensation appears to be centrally located rather than to belong to one ear or the other.

**PITCH MATCHING**

**(1)** *for a two-lobe central array*

When a pure tone pitch matching situation is arranged, with an SL of 25 dB and a pure tone range of 250 Hz to 1 kHz and a range of $\tau$ of 4 to 0.4 msec, the central-pitch producing patterns of Fig. 6 can be divided into two groups. For Figs. 6a and 6b the matches lie along the line $1/\tau = (4/3)^{*} f_s$ where $f_s$, is the frequency of the pure tone given to the subject and to the pitch of which he must adjust the noise by varying $\tau$ . For Figs. 6c and 6d the matches lie along the line $1/\tau = f_s$ and their dispersion is somewhat less. In both cases octave confusions may be made. Once more an alteration of any part of the array will alter the response to the whole. The use of a right handed array, 1 and 3 of Fig. 4, instead of the present left handed configuration, makes no difference to the type or accuracy of pitch matching.

**(2)** *for a three-lobe central array*

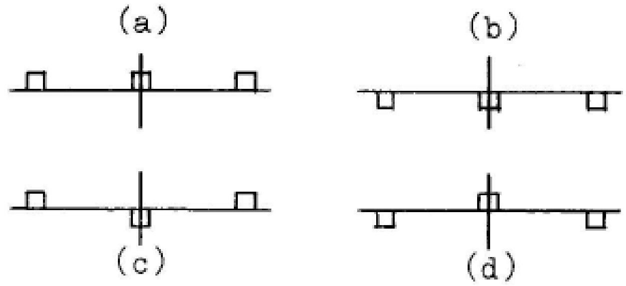


Fig. 7 Centre-symmetric three-lobe lateralization arays

If a right hand lobe is added to the previous array, by means of a third independent noise generator, as in Fig. 4, the use of symmetrical delays and phase changing results in the family of lateralization arrays shown in Fig. 7. Each one of these arrays has a pitch associated with it. Pitch matching as before and again with a 25 dB SL produces exactly the same division as before. Figs. 7a and 7b correspond to Figs. 6a and 6b and Figs. 7c and 7d correspond to Figs. 6c and 6d. Qualitatively the pitch sensation associated with this three-lobe array is just the same as for the two-lobe presentations. A phase-asymmetric three-lobe array has an essentially indistinguishable pitch. The use of extra symmetrical lobes to make a five element array does not improve the clarity of the pitch.

**(3)** *for a two-lobe asymmetric array*

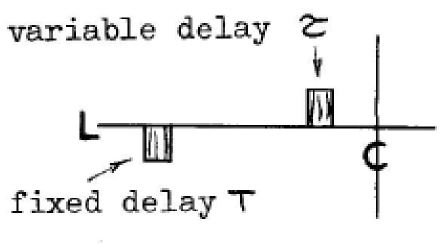


Fig. 8. Asymmetric two-lobe array

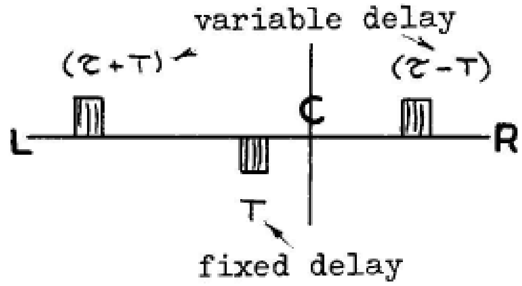


Fig. 9. Centre-asymmetric three-lobe array

When the fixed central lobe of any of the arrays of Fig. 6 is displaced to one side, by an amount *T*, the pitch associated with a change of $\tau$ for the variable lateralization lobe becomes quite different. The array of Fig. 8, for which $\tau < T$, gives a pitch which increases as T is increased. When $|T - \tau| \leq 1$ msec the pitch disappears and re-appears, if $\tau$ is increased beyond T, when the variable lobe is symmetrically on the other side of the fixed lobe. It follows that the pitch is not dependent on the absolute delays employed but can be interpreted in terms of the relative lateralizations of the lobes. Pitch matching with *T*= 3 msec gave the same general results as before for this type of stimulus when the relative delays were plotted, $1/(T - \tau) = f_s$ (but $f_s$ was only in the range 300 Hz to 700 Hz).

**(4)** *for a three-lobe asymmetric array*

In Fig. 9, $\tau$ has been re-defined to give the variable lobe delays relative to those for the fixed lobe. When T = 0·3 msec for this fixed lobe, pitch matching is essentially identical with that for the lobe pattern of Fig. 7c. When T = 1·5 msec matching is more difficult but the basic relation between $\tau$ and $f_s$ is unaltered.

## POSSIBILITY OF AN ARTEFACT

The central pitch which has been described is only of interest if it requires a neural mechanism for its explanation. This need could be dispensed with by showing that the pitch effects described could result from a peripheral analysis. If there is even a small spectral peak in the acoustic stimulus to either or both of the ears, this peak might be resolved in an orthodox way. There are two basic ways in which such a peak might occur. First by an apparatus malfunction such that it is present explicitly in the original stimulus. Second by a physical interaction, cross talk, between the stimuli which takes place only when the subject is wearing the headphones.

**(1)** ***Spurious stimulus pitch.*** Long term spectral analyses (Fourcin, 1964) of the stimuli have been made which are capable of resolving peaks of less than 0.5 dB but no trace of a peak has been found. More convincing evidence is contained in the nature of the experiments themselves, however. When, for any one of the patterns of Fig. 6, the central noise is removed, to one ear or to both, the pitch effect disappears. Now it is easy to provide this noise from a variety of external sources, each of which is quite innocent of spectral peaks and independent of the t-generating apparatus, but with any of them the pitch is restored. In consequence the pitch is a function of this independent noise which, if the pitch were an artefact, would ordinarily be expected to be a source of masking. This only leaves the lateralized lobe, and the results of the free-space experiment show that the pitch is not generated by the particular type of apparatus involved in the production of delay.

**(2)** ***Cross talk.*** Over the range 50 Hz to 10 kHz the interaural attenuation for the subjects and headphones employed was greater than 40 dB. With each lobe stimulus at 25 dB SL the result of interaction is superficially negligible. It is always possible however that an unknown facilitating effect is present in the multiple-lobe presentation which could enhance the effect of cross talk. To investigate this possibility the nature of the pitch which cross talk would produce if it were present (echo pitch, due to noise ± itself delayed) has been separately investigated. Subjects matched echo pitch significantly differently from central pitch (Fourcin, 1965); in consequence the results reported here could not be due to a simple physical interaction between the stimuli.

The most convincing result in favour of the separate existence of a central neurally mediated pitch comes however from the observations made with the lateralization array of Fig. 8. Here the perceived pitch at first increases and then decreases with a steady increase in the delay producing the variable lateralization lobe. This result is quite consistent with the other central pitch observations. It is not possible to reconcile it with a frequency based pitch mediation.

## CONCLUSION

The pitch observations which have been reported here can be neatly classified in terms of lateralization patterns but in no way related to peripheral single ear frequency analysis. In consequence central pitch owes its mediation to a neural mechanism capable of operating on the temporal structure of acoustic stimuli.

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## DISCUSSION

*De Boer*: If you have two noise sources and you connect a different band-pass filter to each output such that the two sounds do not overlap in frequency, do you get this central pitch sensation and does the region of overlap have anything to do with the pitch?

*Fourcin*: The situation you describe could be associated with the two-lobe arrays of Figs. 6 and 8. It was, however, investigated using the arrangement shown in Fig. 5b. If there is no frequency overlap for the two associated noise sources there is no pitch. If the overlap occurs above about 2 kHz there is no pitch. If the overlap is small below 2 kHz then the sensation level and the range of the central pitch are small.

***Piazza:*** Do you think that there is a relation between this effect and binaural beats?

*Fourcin:* Yes. I think both phenomena have a common neural origin but that the effects I have described depend on more processing.

***Plomp:*** Do I understand your paper correctly that the time delays involved in this central pitch are significantly larger than in direct binaural listening with the consequence that we cannot hear this pitch normally?

***Fourcin:*** The maximum interaural delay normally encountered in ordinary binaural listening corresponds to the minimum inter-lobe delay which can lead to a sensation of the present pitch. The maximum interlobe delay associated with a central pitch is about 10 to 15 msec. This also corresponds to the maximum interaural delays for which judgments of sidedness can occur. It is interesting that both this lateralization effect and the central pitch described here cannot occur in normal listening. It seems unlikely that the neural mechanisms which lead to their existence have evolved uselessly. Just as for the sensation of binaural beats, these effects may be the slight by-products of essential components of our auditory processing. I believe that the function of the particular component concerned with central pitch is one of signal analysis-as opposed to detection and localization. The Huggins effect (Cramer and Huggins, 1958) is similar to those described here and I have found it also to be invariant with the type of translation shown in Fig. 8, but although its pitch can be equated with that of the stimuli of this paper its quality is quite different. This quality distinction can only be made as the result of quite elaborate processing in the nervous system. I think it likely that this processing is available in normal listening; not only binaurally but also monaurally and that it mediates the sensations of echo pitch and the really important residue pitch family.

*Wilson:* I was very impressed by the way in which the data points in your slides are closely grouped around the lines you drew. How does the spread for the pitch matchings in your experiments compare with the spread for the pitch of gated noise and for the residue pitch?

*Fourcin:* I have measured the dispersion of the pitch matches made with my stimuli but it is difficult to make an exact comparison with the results which have been obtained using gated noise (Harris, 1963) and with residue pitch stimuli (Cardozo and Ritsma, 1965). This difficulty arises because I have only employed pure tones as reference stimuli, in consequence my subjects have had a more than usually difficult pitch matching situation. The relative standard deviation of their responses however is only a little greater than that associated with residue pitch. In consequence it is much smaller than that for gated noise and significantly greater than that for pure tone matched against pure tone.

*Goldstein:* You said that the lines you drew are theoretical lines. Do you mean you have a theory of central pitch?

Secondly, you stated that your central pitch effect requires very careful listening with both ears. Could you elaborate on that?

*Fourcin:* The lines defined in the paper and shown in the slides are good fits to the experimental matches but they are derived from the idea that the effects are a side-product of a central process of signal-in-noise analysis. I would, however, prefer not to discuss a theoretical explanation of the whole phenomenon at present.

When listening to these stimuli one can either attend to the lateralization images with which they may be associated or to their pitch. In my experience, subjects cannot hear both percepts at once, the one precludes the other. The consequent direction of attention required to hear the pitch is initially not always easily obtained.

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