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MONAURAL SPATIAL INFORMATION : AZIMUTH AND THE EXTERNAL EAR.

Anthony J.Watkins.

Department of Psychology, Reading University.

For many years it has been known that monaurally deaf (or artificially deafened) subjects can detect changes in the azimuth of sound sources (Angell and Fite, 1901) with a minimum audible angle of around 5^{o} (Harris and Sergeant, 1971). Many authors have proposed that the acoustic response of the external ear is asymmetrical at high frequencies and provides information about source azimuth. This idea is supported by the observation that monaural azimuthal localisation is severely impaired when the external ear on the unoccluded side is distorted (Butler, 1975) and when the sound to be localised lacks the higher audio frequency components which interact with the external ear (Belendiuk and Butler, 1975). In other experiments it has been shown that distorting the external ear cues by selective occlusion of the external ear cavities impairs azimuthal localisation even when interaural disparity cues are available (Freedman and Fisher, 1968; Butler, 1975).

Ear canal recordings confirm that the response of the external ear varies with azimuth at high frequencies (Shaw, 1966, 1974a,b; Belendiuk and Butler, 1975) and this raises the question of how this locale 'encoding' is treated by the auditory system.

A special case of azimuthal localisation is front-back discrimination (i.e., 0^{o}/180^{o} azimuthal discrimination) which is significantly above chance for broad band noise sources (Burger, 1958; Blauert, 1969/70). The experiments of Blauert (1969/70, 1971) and Hebrank and Wright (1974) show that the front-back discrimination of sharply filtered noise is systematically biased, in accordance with the similarity between the electrical source filtering and spectral features in the response of the external ear at these locations. Blauert (1969/70) postulated that azimuth is decoded by a process which assesses the relative energy across two sorts of 'directional' frequency bands; a 'v' band (vorne or front) is the spectral region where a high concentration of energy leads to a frontal percept, and a 'h' band (hintern or behind) gives an apparent source location to the rear. The position of these bands is in agreement with the localisation biases observed by Blauert (1971) and Hebrank and Wright (1974) and ear canal recordings show similar changes in spectral energy distribution with azimuth (Blauert, 1969/70; Shaw, 1974b). These data imply that there are general (across subject) aspects of the external ear's asimuthal response. However, Belendiuk and Butler (1975) were unable to see any distinct, general spectral cues for azimuth in their ear canal recodings and they concluded that azimuthal locale decoding is based purely on idiosyncratic features. On the other hand, Batteau (1967, 1968) reports a general external ear cue for azimuth; a short latency echo (τ_A) which decreases monotonically from 80µs (at 0^{o}, 'front') to 0µs at around 90^{o} ('side'). Batteau also reported a second echo (τ_V) which varied from 100µs to 300µs with decreasing elevation and it has already been shown that a system which introduces echoes of these values (i.e,, a 'two delay and add system') has a frequency response closely resembling that of the external ear. Furthermore, when high pass filtered noise is used as input, and the longer latency echo (τ_V) is swept over the 100-300μs range, distinct vertical movement is perceived when the sounds are presented at the observer's ear canal entrance (Watkins, 1978). The latter demonstrates that there are general external ear cues for vertical location; the experiments reported here employ a similar technique to illuminate the nature of the external ear cues for azimuth and to shed light on the locale 'decoding' process.

In a preliminary investigation sounds were prepared in which the longer latency echo, τ_V, was held constant and the shorter latency echo, τ_A, was swept slowly over the 0-80μs range. The results were disappointing; no smooth azimuthal movement was perceived by naïve or experienced listeners. However, azimuthal variations were reported (but not recorded) in experiments where τ_V was dynamically varied and τ_A was held constant; so, in order to investigate the effect of varying τ_A, perceived movement was generated by dynamically varying τ_V while τ_A was fixed within a sequence (trial) but varied between trials. A stimulus sequence consisted of a slow linear sweep of τ_V from its initial value (τ_{VO}) to τ_{VO} + 60μs, then to τ_{VO} - 60μs, before rising to τ_{VO}. The whole sequence lasted 40s. and was reversed on half of the trials. Two values of τ_V were used (176 μs and 215 μs) with six values of τ_A between 0μs and 100μs. The observer was required to indicate the perceived azimuth of the stimulus immediately prior to offset, and this was done by matching perceived azimuth to the azimuth of a pointer which rotated around the ear canal entrance of a life-size dummy head. The results show significant variations in perceived azimuth with τ_A, ranging from 78° to 122°. (Means of ten observers). Batteau's data would lead one to expect a monotonic variation in perceived azimuth with τ_A, from 90° to 0° as τ_A is increased from 0μs to 80μs, but no such relationship was found here.

However, the present data are consistent with Blauert's directional band theory; the spectra of the experimental stimuli show that the most frontal percepts arise when there is relatively more energy in the 'v' bands (front), and the stimuli localised to the rear have relatively more energy in the 'h' band (behind). An interesting relationship which emerges is that frontal images are perceived when $\tau_A = \tau_V/4$, and that locations behind the ear are perceived when $\tau_A = \tau_V/2$, low values of τ_A being perceived around 90° (side). The reason for this is that the values of τ_V used give three peaks in the audible spectrum above 5kHz, at $1/\tau_V$, $2/\tau_V$ and $3/\tau_V$, and these peaks are located in the region of 'v', 'h' and 'v' directional bands respectively. Adding a second echo of latency = $\tau_V/2$ will depress the $1/\tau_V$ and $3/\tau_V$ peaks and boost the $2/\tau_V$ peak, thereby increasing the energy in the 'h' band (behind). Similarly, when the second echo latency = $\tau_V/4$, energy in the 'h' band ($2/\tau_V$) is depressed and the 'v' band ($1/\tau_V$, $3/\tau_V$) energy is boosted.

The above reasoning was employed in the design of a second experiment which compared perceived azimuth at $\tau_A = \tau_V/2$, $\tau_V/4$ and 0, at six values of τ_V between 150μs and 270μs. A prediction derived from Blauert's theory is that perceived azimuth differences across τ_A should be maximal when the peaks due to τ_V lie on the directional bands, and minimal when the troughs due to τ_V lie on the directional bands. The results show just such maxima and minima; when τ_V = 204 μs the range of perceived azimuth was a maximum being 71.2°, 94.4° and 119.5° ($\tau_A = \tau_V/4$, 0 and $\tau_V/2$ respectively) and when τ_V = 268μs the range was a minimum (95.8°, 95.4° and 97.0°; $\tau_A = \tau_V/4$, 0 and $\tau_V/2$ respectively). (Values of perceived azimuth are means of ten observers making two observations each). The directional band centre frequencies derived from the above results lie between 4.6 - 4.9kHz ('v'), 9.3 - 9.8kHz ('h' and 13.1 - 14.7kHz ('V'), and these values are in close agreement with the ear canal recordings of Shaw (1974b) and Blauert (1969/70) and with the localisation results of Blauert (1969/70) and Hebrank and Wright (1974).

In summary, the present experiments demonstrate that changes in perceived azimuth may be generated monaurally with earphone presentation, and the results are seen as providing further support for Blauert's directional band theory.

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