

Auditory Neuroscience: A Time for Coincidence?

Dispatch

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Mammals and birds appear to encode timing differences between the ears, a major cue for auditory localization, in fundamentally different ways. It now appears that results from different species can be accommodated within a single general framework.

An ability to localize sounds both accurately and rapidly – particularly if they occur outside the field of view – is of obvious survival value. Because the afferent nerves from the cochlea do not convey spatial information directly, neural computations have to be performed within the brain in order to determine the direction of a sound source. This involves comparing the intensity and time of arrival of the sound at the two ears. Together with the spectral filtering imposed by the external ear, these binaural cues are responsible for auditory localization [1].

Psychophysical studies in humans have shown that the principal cue for sound localization in the horizontal plane, at least at low frequencies, is the interaural time difference (ITD) [2]. The maximum ITD encountered depends on the distance between the ears; in adult humans it is about 600 μ s. Humans can discriminate ITDs as small as 10–20 μ s [3] – an astonishing achievement given that the duration of an action potential is two orders of magnitude greater than this.

Over the last few years, electrophysiological studies have indicated that the neural basis for ITD coding may vary among different species. Recent modelling data [4], however, suggest that the optimal coding strategy depends primarily on head size and the sound frequency range over which ITDs can be discriminated, rather than a more intrinsic difference between species.

The Jeffress Model: A Neural Mechanism for Localization

Over 50 years ago, Lloyd Jeffress [5] proposed what has become the textbook view of how the brain computes ITDs. He suggested that ITDs could be extracted using a set of binaural coincidence detectors that respond maximally when they receive synchronous excitatory input from each ear (Figure 1). The idea is that different coincidence detectors are tuned to different ITDs within the physiological range – the range determined by head size – and therefore to different horizontal directions. This ITD map can be achieved through a series of ‘delay lines’ produced, for example, by systematically varying the relative

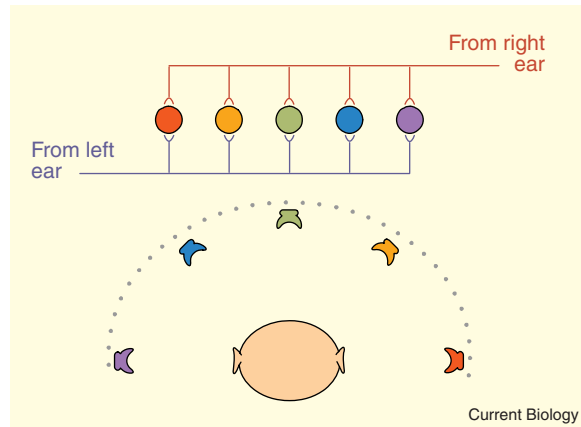


Figure 1. Schematic illustrating the key features of the Jeffress model of ITD coding.

The Jeffress model is based on the convergence of variable length delay lines onto neural coincidence detectors. Each coincidence detector responds maximally to a single ITD and therefore to a single sound source direction in the horizontal plane. For example, the green ‘neuron’ responds best to a sound source located at the midline, because the inputs to this neuron have axons of equal length. The orange and red detectors respond best to sounds from the right, as the longer axons from the right ear compensate for the earlier arrival of sound at this ear.

length of the axonal inputs to the coincidence detectors from each ear. The Jeffress model provides an alluringly simple description of how the brain calculates and represents ITDs, but remained largely hypothetical until the 1980s, when evidence was found for each aspect of the model in the nucleus laminaris of the barn owl [6,7], an accomplished auditory predator.

Calling the Model into Question

Although the Jeffress model has become dogma among many auditory neuroscientists, it does not readily explain all aspects of ITD processing. For instance, a uniform distribution of best ITDs would predict that ITD acuity is the same at all azimuths, and this is known not to be the case [3]. Furthermore, the coding principle described by Jeffress is actually unlike that found in most brain regions, including those containing maps, where information tends to be represented across a population of broadly tuned neurons with overlapping sensitivities [8].

Early studies of the mammalian medial superior olive – the homologue of the owl’s nucleus laminaris – provided support for the Jeffress model [9–12]. More recent evidence, however, points to a different coding mechanism, in which ITD-sensitive neurons fall into two sub-populations, one on each side of the brain, which are maximally sensitive to ITDs outside the range the animal is capable of experiencing [13–15]. What seem to matter for ITD discrimination are therefore the slopes

of the neurons' ITD functions [16] — which do fall within the physiological range — rather than their peak values. This suggests that the rate of change of firing may be more important than the maximum response.

These features are clearly incompatible with the Jeffress model. Another recent discovery is that the ITD tuning of neurons in the gerbil medial superior olive appears to arise, not from delay lines, but from precisely timed inhibitory inputs [14]. Thus, two of the central tenets of the Jeffress model, namely the existence of a uniformly distributed map of best ITD and the dependence of ITD tuning on anatomical delay lines, have been cast into doubt in mammals.

Reappraising Owls and Mammals

A new modelling study [4] now suggests that it may be possible to reconcile the data from owls and mammals. Harper and McAlpine [4] determined the optimal coding strategy in a population of model neurons for the ITDs present in pure tones. For these periodic stimuli, the ITD is manifest as an interaural phase difference (IPD) (Figure 2). Whereas in many neurons the ITD tuning width becomes broader as the frequency is decreased, that of the IPD tuning curve does not [13,15]. This feature was used to simplify the model, because it allowed the authors to assume that the IPD tuning curve of each neuron is Gaussian in shape and essentially the same across frequency and species.

The authors determined the distribution of best IPDs that resulted in the lowest coding error within a population of 200 model neurons. Coding error was estimated by deriving the population's response variance using a traditional measure of coding accuracy, the Fisher information. Fisher information places emphasis on the slopes, rather than the peak, of the tuning curve, because these are the regions over which the firing rate changes most as a function of the stimulus value (in this case IPD). The optimal ITD coding strategy was determined in this fashion for four different species that differ in head size and in the range of sound frequencies over which phase information is available.

For the gerbil, an animal with a small head and an inability to extract IPDs above ~1,500 Hz, the model predicts two populations of IPD-sensitive neurons with peaks outside the physiological range. Not only does this result match single cell recording data from gerbils [14] and guinea pigs [13], it also makes intuitive sense when considered in terms of the physical constraints imposed by head size and sound wavelength. The maximum IPD that can be experienced depends on the frequency of the sound and the size of the head (Figure 2A,B). For an animal with a small head, low frequency sounds cannot produce large IPDs because the separation of the ears is too small relative to the wavelength of the sound.

At low frequencies, the width of the IPD tuning curve exceeds the physiological range (Figure 2B). Placing the peak within this narrow range therefore provides limited information, because the firing rate of the neuron will change little over the natural range of IPDs. By positioning the peaks of the IPD functions

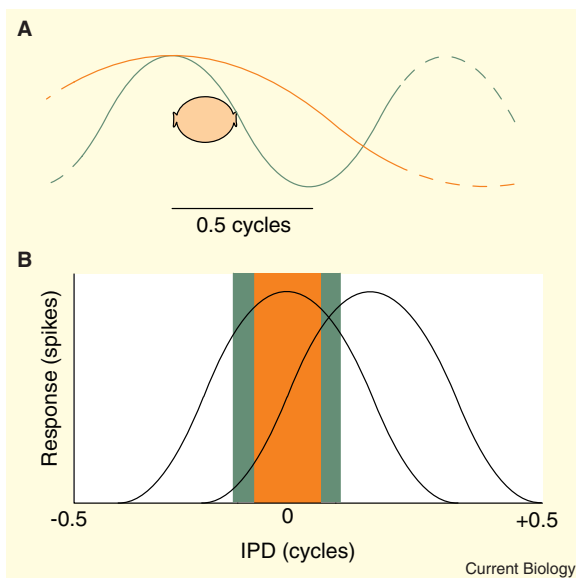


Figure 2. Effect of sound wavelength on the ongoing interaural phase difference (IPD) in low-frequency tones.

(A) The orange and green curves, originating from the same direction to one side, illustrate how the range of IPDs experienced for a given head size depends on sound frequency. The green sine wave has a shorter wavelength and therefore results in a larger IPD compared to the orange wave. (B) Consequently, the physiological range of naturally encountered IPDs is larger at higher frequencies (green bar) than at lower values (orange bar). At low frequencies, in order to make full use of a neuron's dynamic range, the peak of the IPD tuning curves (black curves) needs to be positioned at values that are not encountered naturally.

outside the physiological range, however, the largest variation in firing rate will occur over the IPD range that the animal will actually experience. It is for this reason that Harper and McAlpine's [4] model places simulated gerbil neurons into two sub-populations with peak responses outside the physiological range. This is the configuration that maximizes the Fisher information in situations where the physiological IPD range is restricted.

Applying this analysis to the barn owl — the embodiment of the Jeffress model — produced a rather different result. Although barn owls have a similar head size to gerbils (and therefore experience similar maximum ITDs), they are capable of extracting phase information up to much higher frequencies. This is because the afferent nerve fibres from the cochlea can phase lock — synchronize their discharges to the stimulus waveform — up to ~10 kHz, a feat not seen in any mammal. The physiological range of IPDs is therefore much wider than in gerbils and, from 3–10 kHz, the frequencies used by owls for ITD detection, can accommodate the full range of IPD tuning.

For the owl, the best solution to Harper and McAlpine's [4] model proved to be a homogenous distribution of IPD tuning curves with peak responses (and maximum slopes) within the animal's physiological range. Although the model predicts a Jeffress-like distribution of responses, this solution was based on the same fundamental coding principles as in the gerbil.

Interestingly, at frequencies below 3 kHz, the model predicts that, like the gerbil, the owl should contain distinct sub-populations of IPD-sensitive neurons. Recent recording data provide some support for this [17].

The Demise of the Jeffress Model?

Although the general applicability of Jeffress' model has been called into question, it continues to be a remarkably prescient and stimulating focal point for auditory research. Experimental studies in various species, including barn owls, have required a re-evaluation of the model, bringing in features such as delays in cochlear transmission, phase-locking, inhibitory inputs and broad ITD tuning curves [18,19]. The discovery in small mammals that the slope of the ITD functions may represent timing cues across separate populations of neurons has been used as a strong argument against the Jeffress model. Harper and McAlpine's [4] work puts this into context by showing that these sub-populations conform to the coding principles that were known to exist in the barn owl, for which the Jeffress model is better accepted. Although the mechanisms of auditory localization in barn owls differ in several key ways from those found in mammals [18], this modelling study demonstrates that the basic constraints and coding principles underlying the neural representation of ITD could be more conserved between species than previous results have suggested.

References

1. King, A.J., Schnupp, J.W.H., and Doubell, T.P. (2001). The shape of ears to come: dynamic coding of auditory space. *Trends Cogn. Sci.* 5, 261-270.
2. Wightman, F.L., and Kistler, D.J. (1992). The dominant role of low-frequency interaural time differences in sound localization. *J. Acoust. Soc. Am.* 91, 1648-1661.
3. Yost, W.A. (1974). Discrimination of interaural phase differences. *J. Acoust. Soc. Am.* 55, 1299-1303.
4. Harper, N.S., and McAlpine, D. (2004). Optimal neural population coding of an auditory spatial cue. *Nature* 430, 682-686.
5. Jeffress, L.A. (1948). A place theory of sound localization. *J. Comp. Physiol. Psychol.* 41, 35-39.
6. Carr, C.E., and Konishi, M. (1988). Axonal delay lines for time measurement in the owl's brainstem. *Proc. Natl. Acad. Sci. USA* 85, 8311-8315.
7. Carr, C.E., and Konishi, M. (1990). A circuit for detection of interaural time differences in the brain stem of the barn owl. *J. Neurosci.* 10, 3227-3246.
8. Pouget, A., Dayan, P., and Zemel, R. (2000). Information processing with population codes. *Nature Rev. Neurosci.* 1, 125-132.
9. Goldberg, J.M., and Brown, P.B. (1969). Response of binaural neurons of dog superior olivary complex to dichotic tonal stimuli: some physiological mechanisms of sound localization. *J. Neurophysiol.* 32, 613-636.
10. Yin, T.C.T., and Chan, J.C.K. (1990). Interaural time sensitivity in medial superior olive of cat. *J. Neurophysiol.* 64, 465-488.
11. Smith, P.H., Joris, P.X., and Yin, T.C.T. (1993). Projections of physiologically characterized spherical bushy cell axons from the cochlear nucleus of the cat: evidence for delay lines to the medial superior olive. *J. Comp. Neurol.* 337, 245-260.
12. Beckius, G.E., Batra, R., and Oliver, D.L. (1999). Axons from anteroventral cochlear nucleus that terminate in medial superior olive of cat: observations related to delay lines. *J. Neurosci.* 19, 3146-3161.
13. McAlpine, D., Jiang, D., and Palmer, A.R. (2001). A neural code for low-frequency sound localization in mammals. *Nature Neurosci.* 4, 396-401.
14. Brand, A., Behrend, O., Marquardt, T., McAlpine, D., and Grothe, B. (2002). Precise inhibition is essential for microsecond interaural time difference coding. *Nature* 417, 543-547.

15. Hancock, K.E., and Delgutte, B. (2004). A physiologically based model of interaural time difference discrimination. *J. Neurosci.* 24, 7110-7117.
16. Shackleton, T.M., Skottun, B.C., Arnott, R.H., and Palmer, A.R. (2003). Interaural time difference discrimination thresholds for single neurons in the inferior colliculus of guinea pigs. *J. Neurosci.* 23, 716-724.
17. Wagner, H., Mazer, J.A., and von Campenhausen, M. (2002). Response properties of neurons in the core of the central nucleus of the inferior colliculus of the barn owl. *Eur. J. Neurosci.* 15, 1343-1352.
18. Konishi, M. (2003). Coding of auditory space. *Annu. Rev. Neurosci.* 26, 31-55.
19. Palmer, A.R. (2004). Reassessing mechanisms of low-frequency sound localisation. *Curr. Opin. Neurobiol.* 14, 457-460.