

4. Sound Localization: Birds

Specific cases of CNCs are too controversial to be useful for the purposes of illustrating how MR considerations are irrelevant to assessing the adequacy of mechanistic explanations. Instead, I want to focus on one of the most successful explanatory models in all of systems neuroscience, the neural circuit model of auditory sound localization in the barn owl. For reasons that will become evident shortly, this is a paradigmatic example of a mechanistic explanation. Nevertheless, the capacity to localize airborne sounds is implemented in a diversity of neural mechanisms across different species throughout the animal kingdom. Yet, I will argue, this does not compromise the explanatory status of the model. Nor does it affect the adequacy of any other mechanistic explanations for sound localization in different systems or species. This example helps to show how MR considerations are irrelevant to assessing mechanistic explanations.

Many species of birds are capable of accurately localizing sounds on the basis of auditory cues alone such as during flight in complete darkness. These animals exploit the different arrival times of a sound at the two ears (Figure 8.2). Although these *interaural time differences* (ITDs) may only be microseconds apart, birds have evolved an exquisite strategy to detect and use ITDs to localize sounds. Unraveling precisely how ITDs are computed in the brain is one of the great success stories of modern neuroscience.

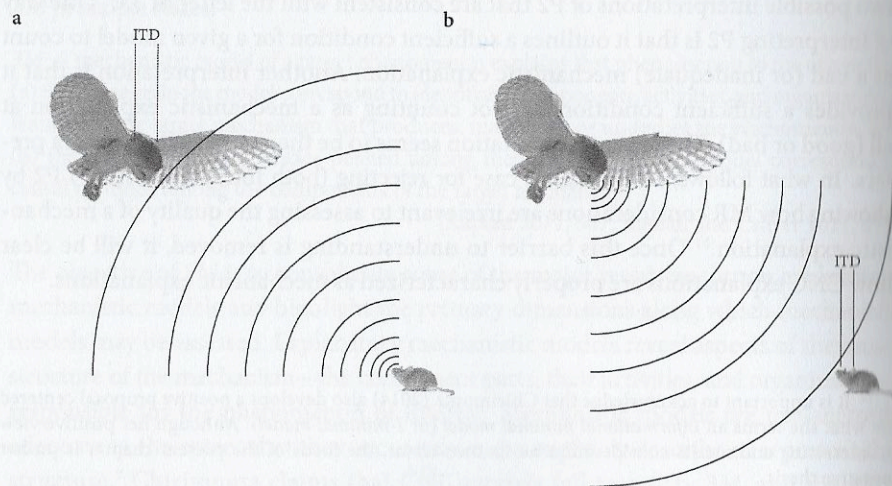


Figure 8.2 Sound localization in birds (A) and mammals (B). Both rely on computing the difference between the arrival times at the two ears (ITD) to localize airborne sounds in the horizontal plane.

Source: Grothe (2003), 2. Adapted with permission from Macmillan Publishers Ltd.

More than fifty years ago, the psychologist Lloyd Jeffress proposed an elegant computational model for sound localization in the horizontal plane (Jeffress 1948). The Jeffress model involves three basic elements: (e1) converging time- or phase-locked excitatory inputs from both ears, (e2) coincidence detectors that respond maximally when signals arrive from each ear simultaneously, and (e3) an arrangement of delay lines with systematically varying lengths from each ear so that different coincidence detectors encode different ITDs (Figure 8.3a).¹² Since neural transmission delay time is directly proportional to an axon's length, tuning for different ITDs can be achieved by having axonal "delay lines" of systematically varying lengths project from each ear onto different individual coincidence detectors. A final, related detail of the model is that the set of coincidence detectors are topographically organized such that adjacent coincidence detectors represent adjacent locations in the horizontal plane (Figure 8.3a, schematically represented by grayscale coding along the sagittal plane). Strikingly, Jeffress developed the model to account for a body of human psychophysical data on sound localization, and did so in the absence of information about the nature of the underlying brain mechanisms.¹³

Remarkably, all of the major elements of the Jeffress delay line model (e1–e3) have now been confirmed in the barn owl (Carr and Konishi 1990; Konishi 2003; Pena et al. 2001).¹⁴ Careful behavioral, anatomical, and physiological investigations have revealed a neural circuit for computing ITDs involving delay line-based coincidence detection of signals from the two ears. More specifically, so-called bushy cells in the left and right nucleus magnocellularis (NM) send time-locked excitatory inputs from each ear, implementing e1 of the Jeffress model. Neurons in the nucleus laminaris (NL), the first station of binaural processing in the avian auditory brainstem, are maximally responsive when ipsilateral and contralateral input signals arrive simultaneously. In other words, these neurons perform coincidence detection, implementing e2 of the model. Individual NL neurons tuned to the same characteristic frequency show different preferred ITDs in virtue of differences in the axonal conduction delays from each ear.¹⁵ Recall that, since the time delay of neural conduction through an axon is directly proportional to its length, neural tuning for different ITDs can be

¹² Temporally coincident inputs can be precisely defined in the model as occurring when the sum of acoustic and neural transmission delays originating from one ear equals that from the other ear: $A_i + N_i = A_c + N_c$, where A indicates the auditory input signal, N indicates the neural transmission delay, and subscripts i and c indicate ipsilateral and contralateral, respectively. For further discussion, see Konishi (2003).

¹³ As the original Jeffress model involved a set of minimally constrained mechanistic conjecture about how sound localization might be performed, it constitutes a clear example of a *how-possibly* mechanistic model (Craver 2007; Kaplan 2011).

¹⁴ Although the model was originally verified in the owl, extremely similar observations have been confirmed in most other bird species (Grothe and Pecka 2014).

¹⁵ Frequency tuning is observed in NL and in many other auditory neurons mainly because hearing begins when the cochlea mechanically filters incoming sounds into separate frequency components. Consequently, all output signals from the cochlea are already broken down or filtered according to their various frequencies.

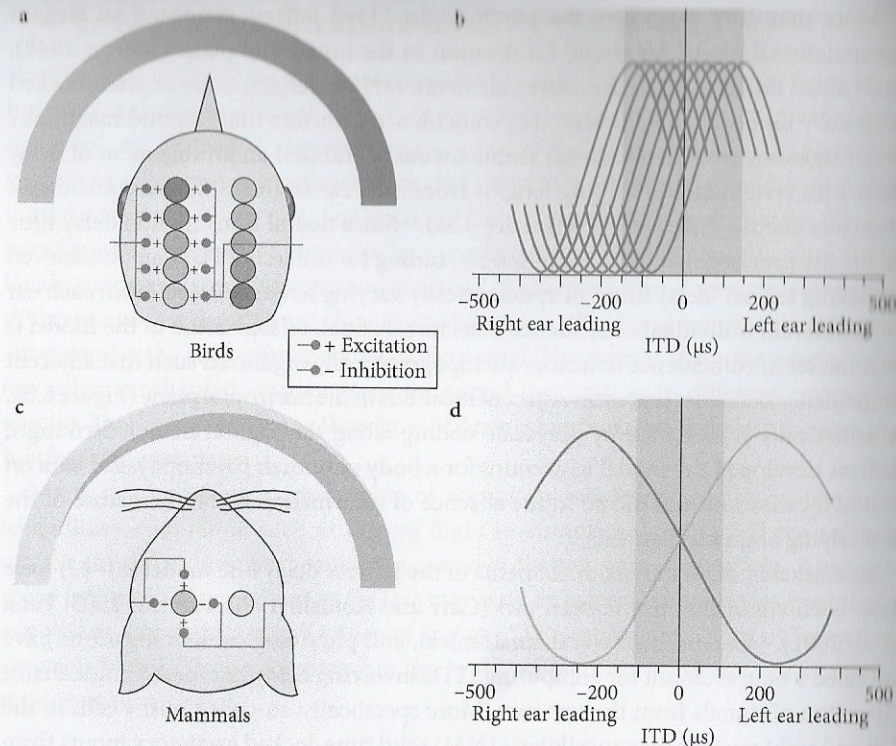


Figure 8.3 Neural computation of interaural time differences (ITDs) in birds and mammals. (A) Jeffress-type computational mechanism observed in the nucleus laminaris (NL) of birds involving coincidence detection of excitatory inputs from the two ears. (B) Distribution of different preferred ITDs across a population of narrowly tuned individual neurons in one hemispheric NL. Shaded area indicates physiologically relevant range of ITDs. (C) Computational mechanism in mammals involving precisely timed hyperpolarizing inhibition that adjusts the timing of excitatory inputs to coincidence detector neurons in the medial superior olive (MSO). (D) For a given frequency band, the ITD tuning of the population of MSO neurons in the left MSO is the inversion of that of the corresponding population of neurons in the right MSO

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implemented by axons (“delay lines”) of systematically varying lengths projecting from each ear onto individual NL neurons. And this is exactly what has been found. A matrix of NL neurons receives inputs from axons of systematically varying lengths (and with systematically varying interaural delays) project along the length of the nucleus, implementing *e3* of the Jeffress delay line model (Figure 8.3a).¹⁶ Because

¹⁶ To make the critical role played by delay lines and coincidence detection clear, it is helpful to consider how different arrangements of delays from the two ears give rise to coincident inputs from different locations in auditory space. For example, axons of equal length projecting from each ear onto a coincidence detector

different NL neurons have different preferred ITDs, a population code is required to represent the entire physiologically relevant range of ITDs (Figure 3b),¹⁷ and by extension, the entirety of horizontal auditory space.¹⁸

Critically, the neural circuit model of sound localization developed by Konishi and colleagues is a paradigmatic example of a mechanistic explanation in computational neuroscience. Its explanatory status is beyond reproach within the neuroscience community, and more importantly it exhibits all the hallmarks of an adequate mechanistic explanation. In particular, it readily satisfies 3M. There is a clear mapping from elements of the model onto all key aspects of the target mechanism in the avian auditory system. The parts, activities, and organization identified in the model are implemented by corresponding structures, activities, and organizational features in the avian brainstem. NL neurons function as coincidence detectors and axons from NM neurons serve as delay lines. Different individual coincidence detector neurons in NL exhibit different response or tuning properties such that across the population the full range of physiologically relevant ITDs are encoded. Finally, the temporal and spatial organization depicted in the model is precisely reproduced in the avian brainstem circuitry. As described in detail above, the timing of excitatory inputs received by individual NL coincidence detector neurons reflects the exquisite spatial organization of axons (i.e., component parts) that are systematically arranged such that their lengths generate neural transmission delays that precisely offset specific ITDs. This organization is essential to their ITD tuning properties.

One way of elucidating why mechanistic models have explanatory force with respect to the phenomenon they are used to explain appeals to the same sorts of considerations that one might plausibly appeal to for other kinds of causal explanations. Along these lines, adequate mechanistic explanations allow us to answer a range of *what-if-things-had-been-different questions* (or w-questions) just as causal explanations do (Kaplan 2011; Kaplan and Craver 2011; Woodward 2005). Purely descriptive models may either fail to provide answers to w-questions and offer no explanation at all, or answer only

neuron in NL will have equal internal neural conduction delays (Figure 8.3a, central row positions); and consequently will give rise to coincident inputs only when sounds are emitted from straight ahead and reach both cochlea at the same time (i.e., when ITD = 0). Because these neurons fire maximally for ITDs of zero, they are said to be tuned or have a best or preferred ITD of zero. By contrast, an NL neuron receiving a short axonal projection from the left (ipsilateral) ear and a long axonal projection from the right (contralateral) ear, will receive coincident inputs and exhibit tuning only for sounds coming from the right auditory hemifield. This is because signals from the right ear must travel longer compared to those from the left. Hence, the internal transmission delays precisely offset the difference in arrival times at the two ears. Conversely, an NL neuron with a short axonal projection from the right ear and a long axon from the left ear will receive coincident inputs and exhibit tuning for sounds coming from the left auditory hemifield.

¹⁷ What comprises the physiologically relevant range of ITDs is determined by factors such as overall head size, and more specifically, the distance between the ears.

¹⁸ It turns out that these neurons are also topographically organized in NL, such that neurons in adjacent positions in NL code for spatially adjacent locations in contralateral auditory space, thereby implementing another detail of the Jeffress model (Figure 8.3a).

a very restricted range of w-questions and offer superficial explanations. By contrast, deeper mechanistic explanations afford answers to a broader range of w-questions concerning interventions on the target mechanism than do more superficial ones. The model for sound localization in the barn owl is an example of a deeper mechanistic explanation. The model allows us to answer a multitude of w-questions. For example, it can answer how the response profile of a given coincidence detector neuron in NL would change if we intervened to vary the length of either the contralateral or ipsilateral axonal delay line through which it receives its inputs. It can answer how the neural circuit would perform if excitatory inputs from one of the two ears were completely or partially eliminated. It can answer the question of which individual coincidence detector neuron in NL would respond if set the ITD value of a sound was artificially set to x microseconds. And so on. Mechanistic models explain because they deliver answers to these and other w-questions.

5. Sound Localization: Mammals

For many years, it was thought that all birds and mammals perform sound localization by relying on the same Jeffress-type mechanism involving coincidence detection of excitatory inputs coming from the two ears. However, mounting evidence now suggests that mammals compute ITDs and thereby localize sounds using a different underlying mechanism. It is becoming increasingly clear that mammals (unlike birds) do not rely on a population of neurons with a precise arrangement of axonal delay lines from the two ears in order to compute ITDs and perform auditory localization (Ashida and Carr 2011; Brand et al. 2002; Grothe 2003; McAlpine and Grothe 2003; McAlpine et al. 2001; Myoga et al. 2014).¹⁹ Instead, the emerging picture attributes a major role for synaptic inhibition in the processing of ITDs (Figure 8.3c). More specifically, precisely timed hyperpolarizing inhibition controls the timing of excitatory inputs reaching binaural coincidence detector neurons in the mammalian auditory brainstem structure known as the medial superior olive (MSO).²⁰ Inhibition slows the transmission of excitatory inputs to the MSO in such a way as to precisely offset the difference in arrival time at the two ears arising from the specific location of a sound source. This altered temporal sensitivity of binaural neurons in the MSO provides the basis for ITD computation. The fact that excitatory inputs from both ears would reach the MSO without any significant interaural conduction delays (and thus would always coincide at ITDs of zero) in the absence of inhibition, clarifies its role in ITD computation. Mammalian sound localization therefore reflects the convergence of bilateral excitatory and exquisitely timed inhibitory inputs onto coincidence detector neurons in the MSO (Figure 8.3c).

¹⁹ The synaptic inhibition model has primarily been described in gerbils and guinea pigs. However, there is evidence that similar neural mechanisms for ITD computation are at work in other mammals including cats and possibly even humans. For additional discussion, see Grothe (2003) and Thompson et al. (2006).

²⁰ The MSO receives bilateral excitatory inputs from so-called spherical bushy cells in both ventral cochlear nuclei. For additional discussion of the neural circuit underlying sound localization in mammals, see Grothe (2003).

The mechanism underlying ITD computation and sound localization in mammals differs from the mechanism observed in birds in several major ways. First, even though the inhibitory mechanism involves similarly functioning parts (i.e., neurons serving as coincidence detectors), the functional activities—tuning properties—of coincidence detector neurons in MSO are fundamentally different from those observed in the avian auditory system. Specifically, individual MSO neurons do not have different preferred ITDs distributed across the entire relevant range of ITDs, as is found in birds (Figure 8.3b). In mammals, all MSO neurons tuned to the same frequency band within each hemispheric MSO exhibit the same ITD tuning, and horizontal sound location is read out from the population-averaged firing rate across two broadly tuned spatial channels—one for each hemispheric MSO (Figure 8.3d). What this means is that a change in the horizontal position of a sound source will induce a specific pattern of change in population activity in one hemisphere and a corresponding change of *opposite sign* in the population activity in the other hemisphere. For example, a sound moving away from the midline (where ITD = 0), might serve to increase activity in the contralateral MSO and correspondingly decrease activity in the ipsilateral MSO, thereby indicating that the sound source has shifted to a more lateral position. It is therefore the relative difference between the two hemispheric channels (the relative activity across the entire population of MSO neurons) that encodes ITD information and indicates the horizontal location of a sound source. Because individual MSO neurons within each hemisphere carry similar information, this argues against the local coding strategy observed in birds in which each individual neuron encodes information about different ITDs, and instead strongly implies that a population code is used to represent ITDs (Lesica et al. 2010; McAlpine et al. 2001).

Second, the mammalian mechanism for ITD computation involves different parts doing different things. As indicated above, in addition to the excitatory projections originating from the left and right cochlea, MSO neurons also receive bilateral inhibitory projections from other structures in the auditory system that are highly specialized to preserve the fine temporal structure of auditory stimuli with high precision.²¹ These structures generate temporally accurate patterns of inhibition that precisely control the timing of excitatory inputs reaching the MSO.

Third, and perhaps most obviously, certain key parts and properties of the mechanism for computing ITDs in birds are simply missing from the inhibitory mechanism found in mammals. Specifically, there are no axons serving as delay lines. Axon lengths are roughly equivalent such that excitatory inputs from both ears would reach the MSO without any appreciable interaural conduction delay in the absence of inhibition, and thus always coincide at ITDs of zero. It is only through precise inhibitory control over excitatory timing that appropriate ITD tuning is achieved.

²¹ Glycinergic neurons in the medial nucleus of the trapezoid body provide the main source of hyperpolarizing inhibition to the mammalian MSO. For further discussion, see Grothe (2003).