

UC Irvine

UC Irvine Previously Published Works

Title

Chapter 5 Human Auditory Cortex

Permalink

<https://escholarship.org/uc/item/5nm8k618>

Authors

Barton, Brian
Brewer, Alyssa A

Publication Date

2016

DOI

10.1016/b978-0-12-407794-2.00005-5

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

Human Auditory Cortex

Brian Barton^{1,2} and Alyssa A. Brewer^{1,2,3}

¹Department of Cognitive Sciences, University of California, Irvine, Irvine, CA, USA; ²Center for Cognitive Neuroscience and Engineering, University of California, Irvine, Irvine, CA, USA; ³Center for Hearing Research, University of California, Irvine, Irvine, CA, USA

5.1 INTRODUCTION

One of the fundamental discoveries of neuroscience is that sensory regions of cortex are formed of many functionally specialized areas that are organized into hierarchical networks (Kaas & Hackett, 2000; Krubitzer, 2007; Schreiner & Winer, 2007; Van Essen, Felleman, DeYoe, Olavarria, & Knierim, 1990). The simplest features are processed in low-level areas that then pass that information up the hierarchy to perform increasingly complex computations. A general feature of these systems is that the topography of the sensing organ represents the most fundamental stimulus information, which is preserved through much or all of the hierarchy (Brewer & Barton, 2012). It has been suggested that this preservation of topographical organization allows for efficient connectivity between neurons that represent nearby portions of sensory space, likely necessary for processes such as lateral inhibition and gain control (Chklovskii & Koulakov, 2004; Mitchison, 1991; Moradi & Heeger, 2009; Shapley, Hawken, & Xing, 2007). From a researcher's perspective, this topographic preservation allows us to use one set of stimuli to localize a number of sensory areas rather than designing specialized stimuli for each sensory area (Brewer & Barton, 2012).

Many details remain to be elucidated in each cortical network, and it is the goal of this chapter to provide an overview of the current understanding of the cortical organization of the low-level sound processing areas of the human auditory system. It is not within the scope of this chapter to discuss the organization of the entire human auditory system; we only touch on the subcortical areas and higher-order processing areas. However, we note that low-level cortical organization has much to teach us about both subcortical and higher-order processing areas.

Researchers have long been aware that low-level auditory processing occurs on and near Heschl's gyrus (HG) of the human temporal lobe in the lateral (Sylvian) fissure, but many questions have remained unanswered. How many distinct auditory areas exist in this region? What is the proper method to functionally localize these areas? Which computations are performed in which areas?

5.2 CORTICAL FIELD MAPS

The accurate delineation of cortical areas is important to review here. Cortical areas have traditionally been identified in visual cortex, the most studied of the sensory cortices, based on a combination of the following measurements: (i) cytoarchitecture; (ii) connectivity patterns; (iii) cortical field topography; and (iv) functional characteristics. This definition has led to many controversies because these measurements have conflicted at times. Thus, in vision and in audition, investigations have primarily been limited to the measurement of cortical field maps (arising from topographical measurements), which is the principal measurement of cortical areas in the *in vivo* human brain currently available.

The presence of a cortical field map is established according to several criteria. First, by definition, each cortical field map contains a single representation for each point in the sensory domain (DeYoe et al., 1996; Press, Brewer, Dougherty, Wade, & Wandell, 2001; Sereno et al., 1995; Wandell, Dumoulin, & Brewer, 2007). For this to be valid, orthogonal gradients of fundamental sensory dimensions must comprise each field map (Brewer & Barton, 2012; Wandell et al., 2007). In addition, each field map should represent a substantial

portion of sensory space, although cortical magnification of specific subsets of sensory space and measurement limitations may reduce the measurable portion. Second, each representation of the sensory domain must be organized as an orderly gradient that is generally contiguous. Third, the general features of the gradient representations comprising the field maps should be consistent across individuals. It is important to note, however, that even well-accepted cortical field maps in visual cortex can vary dramatically in size and anatomical location (Brewer, Liu, Wade, & Wandell, 2005; Dougherty et al., 2003). Even so, the topographical pattern of adjacency among specific cortical field maps should be preserved across individuals.

An important step forward in understanding the organization of human auditory cortex was the recent discovery of 11 auditory field maps (AFMs) on HG (Barton, Venezia, Saberi, Hickok, & Brewer, 2012). These measurements provide an important framework for the organization of individual AFMs in humans as well as the organization of the AFMs with respect to one another. Whereas this information still leaves much to be discovered, it is a fundamental rethinking of the organization of auditory cortex that has implications that resonate throughout the auditory processing hierarchy.

In particular, this rethinking has important implications for speech perception, which occurs at the upper end of the auditory processing hierarchy (Hickok & Poeppel, 2007). To date, research of the neural basis of speech perception overwhelmingly emphasizes the identification of relatively high-level auditory systems that are specialized for coding speech categories (e.g., phonemes). Such work often compares the cortical response to speech with various acoustic controls to factor out low-level acoustic processes. While valuable, this approach ignores the fact that the input to these higher-level systems is derived from an acoustic signal that is already highly processed. Our increased understanding of the inputs to speech perception systems is critical to understanding what kind of categorical information is ultimately extracted from the speech stream and, from a computational perspective, how that information is extracted (Poeppel, Emmorey, Hickok, & Pylkkanen, 2012).

5.3 TONOTOPY: THE FIRST DIMENSION OF AFMs

Beginning in the ear, the auditory system takes a complex sound wave and breaks it down into individual component frequencies, analogous to a Fourier analysis (Spoendlin, 1979). A topographic gradient of low-to-high frequencies, or tones, is referred to as tonotopy (or less commonly, cochleotopy). This basic auditory information and tonotopic organization are

preserved through multiple subcortical areas and in low-level auditory cortex (for review, see Ress & Chandrasekaran, 2013; Saenz & Langers, 2014).

Each small band of frequency channels is thus processed largely independently of the others in its own computational pipeline and can be thought of as a common topographic reference frame between individual areas. Tonotopy is thus one aspect of the fundamental auditory reference frame. Each auditory area performs one or more computations across the entire reference frame, such as sound onset, offset, duration, intensity, localization, and others. The degree to which tonotopy is preserved remains unclear above the lower levels of the hierarchy (Barton et al., 2012; Humphries, Liebenenthal, & Binder, 2010; Kaas & Hackett, 1998). However, it would be surprising if this information were only preserved to a certain point of the system and then abolished (Brewer & Barton, 2012). It is much more efficient to put that information to use, even if it is only a part of the information necessary to perform a high-order computation.

Although this understanding of one aspect of the auditory reference frame is important, it is incomplete for the purposes of delineating individual AFMs (Barton et al., 2012; Brewer & Barton, 2012; Wandell, Brewer, & Dougherty, 2005; Wandell et al., 2007). To identify tonotopic gradients using a single set of stimuli that activate most or all of the maps, researchers present an array of pure tones (or tone complexes or narrowband noise; Barton et al., 2012; Da Costa et al., 2011; Formisano et al., 2003; Humphries et al., 2010; Sweet, Dorph-Petersen, & Lewis, 2005; Talavage et al., 2004; Upadhyay et al., 2007; Woods et al., 2010). However, tonotopy is one-dimensional, whereas the cortical surface, on which we would like to draw the boundaries between auditory areas, is two-dimensional. Thus, any tonotopic gradient with a given width can be divided into any number of arbitrary individual areas with a complete low-to-high tonotopic gradient (Figure 5.1). As such, we can be certain that auditory areas exist where tonotopic gradients exist, but their number and characteristics require additional measurement, as described. To accurately define an AFM, measurements of a second dimension of the auditory reference frame that is orthogonal to tonotopy are needed (Barton et al., 2012; Brewer & Barton, 2012). Auditory researchers have lacked confirmation of a second dimension until recently; as such, they have relied heavily on complimentary methods that are invasive and typically performed using animal models.

5.4 CORTICAL ORGANIZATION OF THE MONKEY AUDITORY SYSTEM

In monkeys, a standard model of the cortical auditory system has been developed through a

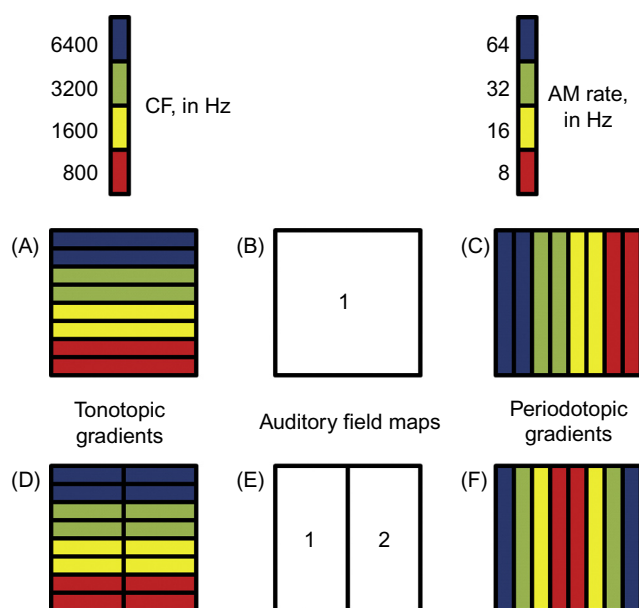


FIGURE 5.1 Orthogonal tonotopic and periodotopic gradients. A cartoon representation of a flattened section of the cortical surface to demonstrate the delineation of AFMs. Inset color legends indicate preferred frequency (tonotopy) or AM rate (periodotopy). The top row is an example showing one AFM existing in the area (B), whereas the bottom row is an example showing two existing in the area (E). (A) and (D) Examples of a tonotopic gradient in the area. Note that without the additional information contained in the periodotopic gradients, it is impossible to know whether there are one, two, or more AFMs in the area. With the information contained in (C), one could conclude that there are orthogonal tonotopic and periodotopic gradients; therefore, one AFM exists in that location (B). Similarly, a combination of the tonotopic gradients in (D) with the periodotopic gradients in (F) would yield two AFMs in the area (E).

convergence of evidence drawn from postmortem cytoarchitectural measurements and tracer studies of anatomical connectivity (de la Mothe, Blumell, Kajikawa, & Hackett, 2006; Fullerton & Pandya, 2007; Hackett, Preuss, & Kaas, 2001; Kaas & Hackett, 1998, 2000), *in vivo* neurophysiological recordings from penetrating electrodes (Kusmirek & Rauschecker, 2009; Merzenich & Brugge, 1973; Morel, Garraghty, & Kaas, 1993; Rauschecker & Tian, 2004; Tian & Rauschecker, 2004), and fMRI measurements (Petkov, Kayser, Augath, & Logothetis, 2006; Petkov, Kayser, Augath, & Logothetis, 2009; Tanji et al., 2010). The model consists of a core comprising three auditory areas (A1, R, and, with less certainty, RT) surrounded by a belt of eight auditory areas (CM, RM, MM, RTM, RTL, RL, AL, and CL). The axis of orientation in the monkey model is indicated by the naming scheme, whereby areas are named by location with respect to A1. The caudal portion of the core is area A1, whereas the more rostral portion contains areas rostral (R) and rostral temporal (RT). The anatomical naming scheme has been adopted for the other maps as well,

with four medial and four lateral maps in the belt encircling the core. Several additional areas have been proposed to comprise the parabelt region abutting the belt region (Kaas & Hackett, 2000; Sweet et al., 2005; Tanji et al., 2010), but these areas are not discussed further here because they are not yet relevant for comparison with the current understanding of human AFMs.

The concept of a “core” can generally be ascribed to studies of cytoarchitectural staining and thalamic inputs, which locate a primary-like region of initial auditory processing along monkey superior temporal gyrus (STG; for review see Kaas & Hackett, 2000). Within the definition of the core, three areas, A1, R, and RT, have further been differentiated on the basis of three tonotopic gradients, with one complete gradient per area. These three gradients are oriented in a “high-to-low-to-high” pattern, with high tones represented in the broadly caudal aspect of A1 and low tones in the broadly rostral aspect that is mirrored in R. RT then mirrors R, which creates two abutting tonotopic gradients that reverse from one gradient to the next at the shared boundary between the areas (Figure 5.3). These gradients were measured using electrode penetrations and recordings from relatively small numbers of neurons and later confirmed by measurements of tonotopy using fMRI in monkey (de la Mothe et al., 2006; Kaas & Hackett, 1998, 2000; Kusmirek & Rauschecker, 2009; Merzenich & Brugge, 1973; Morel et al., 1993; Petkov et al., 2006, 2009; Rauschecker & Tian, 2004; Tian & Rauschecker, 2004). In the belt, some areas have been proposed to contain more coarsely organized tonotopic gradients; however, the tonotopy in other belt areas have primarily been measured using fMRI, and thus assume the boundaries between AFMs in the core and belt without directly measuring them with two orthogonal gradients, leaving open the exact organization of each area (Petkov et al., 2006, 2009; Tanji et al., 2010; Tian & Rauschecker, 2004). Furthermore, it is always possible that there are differences among the species of primate studied (Hackett et al., 2001; Kaas & Hackett, 1998, 2000).

5.5 CORTICAL ORGANIZATION OF THE HUMAN AUDITORY SYSTEM

Naturally, the model of low-level auditory cortical organization in the human is largely a transposition of the monkey model. However, the macaque monkey brains typically studied are much smaller than human brains and diverged from human development during evolution more than 25 million years ago (Kumar & Hedges, 1998). As such, the homology of cortical areas among species is not immediately apparent, nor should we assume that the monkey model is a correct

representation of the human cortical organization. Rather, the monkey model should be viewed as an especially useful but approximate model of human cortex, where differences are expected.

Similar, yet not identical, cytoarchitectural features of core and belt in macaque STG indicate that HG should be the location of the auditory core and belt in humans. Similar cytoarchitectural techniques that identified monkey core reveal in humans a homologous auditory core region on HG, surrounded by regions similar to monkey belt (Dick et al., 2012; Fullerton & Pandya, 2007; Galaburda & Sanides, 1980; Rivier & Clarke, 1997; Sweet et al., 2005). These results suggest that human and monkey STG are not perfectly homologous, with perhaps a portion of monkey STG evolving into human HG. The same data suggest that the human analogue to CM is located on the medial wall of the lateral fissure, near the tip of HG. This is important, because it anchors the expected orientation of the maps from a strictly rostral–caudal axis for A1 to R to RT in monkeys to a medial-lateral axis in humans.

The majority of measurements of low-level auditory cortex are measures of tonotopy using sets of pure tones, tone bursts, tone complexes, and narrowband noise (Da Costa et al., 2011; Formisano et al., 2003; Humphries et al., 2010; Saenz & Langers, 2014; Sweet et al., 2005; Talavage et al., 2004; Upadhyay et al., 2007; Woods et al., 2010). The data across these studies are actually quite similar, but the models put forth based on the interpretation of the data vary widely. In all cases, there is a central low-frequency representation centered on HG with increasing frequencies represented in surrounding bands that form an approximately circular shape. In some cases, portions of the circle are weak, such that the higher-frequency bands resemble a horseshoe shape nearly encircling the low frequencies (Humphries et al., 2010). It is likely that higher-order auditory areas also contain tonotopic gradients, because it is unlikely that the tonotopic information has simply been discarded at this level of processing. Such a persistence of topographic organization into higher-order sensory processing regions has now been measured in the visual system (for reviews, see Brewer & Barton, 2012; Wandell et al., 2007).

Sometimes different naming schemes for these tonotopic measurements of auditory areas have been adopted, but the majority of studies place A1 on the medial or posterior aspect of HG (Da Costa et al., 2011; Formisano et al., 2003; Humphries et al., 2010; Sweet et al., 2005; Talavage et al., 2004; Upadhyay et al., 2007; Woods et al., 2010). Then, R is placed variably on the lateral or anterior aspect of HG, depending on where the strongest “high-to-low-to-high” tonotopic reversal pattern can be identified. Sometimes the “high-to-low-to-high” pattern is a relatively straight path, but in

other cases it is bent. Typically, researchers have guessed at boundaries of cortical areas based on the tonotopic gradient and the potentially homologous monkey model, resulting in either a medial–lateral (consistent with the cytoarchitecture) or anterior–posterior axis of orientation (Da Costa et al., 2011; Formisano et al., 2003; Humphries et al., 2010; Sweet et al., 2005; Talavage et al., 2004; Upadhyay et al., 2007; Woods et al., 2010). In sum, there has been little agreement on how to interpret the similar datasets; there are simply too many ways to interpret sets of one-dimensional gradients when trying to divide them on the two-dimensional cortical surface (for review of similar issues in visual cortex see Brewer & Barton, 2012; Wandell et al., 2007).

5.6 PERIODOTOPY: THE SECOND DIMENSION OF AFMs

Converging evidence suggests that the human homologue of monkey auditory core is located on HG, but the fact that tonotopy is one-dimensional makes it difficult to use tonotopic gradients alone to identify AFMs. An orthogonal gradient is necessary, but for that another fundamental type of information that is a component of the auditory reference frame must be identified. Humans can differentiate sounds based on their pitch, temporal information, loudness, and timbre. Of these, timbre is very likely a process of recognizing combinations of the other three characteristics when one differentiates a tone played by, for example, a flute or an oboe; thus, it is thought that this is unlikely to be part of the fundamental auditory reference frame, but more likely processed along specific computational processing pathways in auditory cortex (Menon et al., 2002; Rauschecker & Scott, 2009; Zatorre, Belin, & Penhune, 2002). Intensity is a good candidate; it is used in sound localization (Middlebrooks & Green, 1991) (i.e., comparing intensity of the same sound detected by each ear) and sound motion localization (McBeath & Neuhoff, 2002) (e.g., the Doppler effect). However, intensity is very similar to brightness in the visual domain, which is not one of the fundamental gradients used to identify visual field maps (VFMs), and it is encoded in the cochlea and potentially in cortex as increases in firing rates of tonotopically tuned neurons rather than in a gradient organization (Shapley et al., 2007; Spoenclin, 1979; Tanji et al., 2010; Wandell et al., 2007).

Recent human psychophysical studies indicate that there are separable filter banks (neurons with receptive fields or tunings) for not only frequency spectra (as expected given tonotopy) but also temporal information (Dau, Kollmeier, & Kohlrausch, 1997; Ewert & Dau,

2000; Hsieh & Saberi, 2010). Furthermore, gradients based on temporal information have recently been discovered in cat primary auditory cortex and the macaque midbrain (Baumann et al., 2011; Langner, Dinse, & Godde, 2009). In addition, such gradients, known as periodotopic gradients, were measured in both cases to be in the same location as, but orthogonal to, tonotopic gradients. Periodotopy refers to the topographic organization of neurons that respond differentially to sounds of different temporal envelope modulation rates.

Inspired by these studies, Barton et al. (2012) recently presented amplitude-modulated (AM) broadband noise to human subjects to measure the cortical periodotopic responses in humans using fMRI. With these stimuli, temporal duration refers to the length of time from peak-to-peak of the AM noise. This stimulus is designed to activate neurons with tuning to sounds that last for a particular duration; in other words, the stimuli differentiate temporal tuning. These stimuli likely drive neurons that respond to the onset and offset of sounds with different amounts of lag time before they can be reactivated, as well as neurons that respond to sounds that exist for a certain duration. Like the monkey and cat studies, Barton et al. (2012) also presented tonotopic mapping stimuli (narrowband noise with varying AM rates) to the same subjects and investigated the responses in low-level auditory cortex.

Three primary findings resulted from the work of Barton et al. (2012). First, temporal information is the second fundamental type of sound information of the human auditory reference frame, complimenting spectral (frequency) information. Second, tonotopy and periodotopy are represented orthogonally to one another in human cortex, allowing for the localization of individual AFMs. By identifying both tonotopic and periodotopic gradients in the same locations and measuring that these gradients are orthogonal to one another, Barton et al. (2012) were able to localize 11 independent AFMs that largely resemble the 11 AFMs of the monkey model (Figure 5.3). Taking into account many characteristics of their data, as well as the correspondence to the monkey model and the underlying human cytoarchitecture, they named each of the AFMs based on those of the monkey model (hA1, hR, hML, hAL, hMM, hRM, hCM, hCL, hRT, hRTM, and hRTL). Because the monkey areas were named based on orientation and because the human AFMs are oriented medial–lateral rather than caudal–rostral, the human AFMs are only the abbreviated letters, not the full title used for monkeys (e.g., hRM stands for human RM, not human rostral medial), and “h” has been appended to mean “human.” Third, these individual AFMs are organized into at least one “clover leaf” cluster (see Section 5.8) (Figures 5.2 and 5.3).

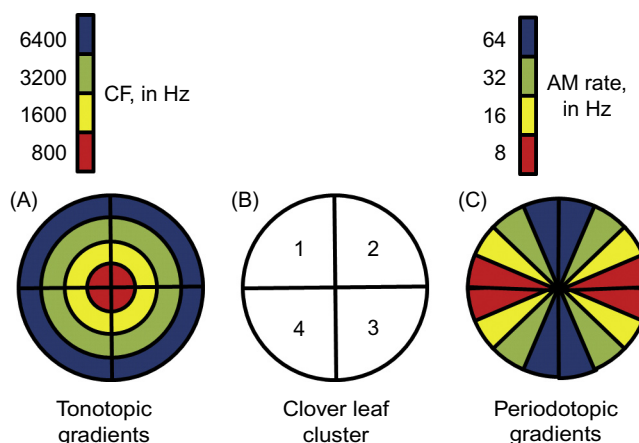


FIGURE 5.2 “Clover leaf” cluster organization. A cartoon example of a “clover leaf” cluster of AFMs on a flattened section of the cortical surface. Inset color legends indicate preferred frequency (tonotopy) or AM rate (periodotopy). This example contains four AFMs, indicated in (B). (A) Each AFM has a complete tonotopic gradient organized such that low-frequency bands are represented in the center of the cluster, with increasing frequencies represented in more peripheral bands of the cluster. (C) Each AFM also has a complete periodotopic gradient organized such that all AM rate bands span from the center to the periphery of the cluster like spokes on a wheel. Each AFM thus has orthogonal tonotopic and periodotopic gradients.

5.7 SIMILARITIES TO AFM ORGANIZATION IN THE HUMAN VISUAL SYSTEM

Visual information is pooled in a series of steps in the retina before being passed through the optic nerve to the thalamus. From there, this information is passed through optic radiations to primary visual cortex into an area known as V1. From there, visual information branches out to visual areas that perform various computations in a generally hierarchical manner from low-level simple visual feature processing to high-level complex feature analysis (for review see Dacey, 2000; Van Essen et al., 1990).

Several characteristics are shared between these areas. At each area, one or more computations are performed for locations of varying size across the entire visual scene (Brewer et al., 2005; Van Essen et al., 1990; Wandell, 1999; Wandell et al., 2005, 2007). These computations are performed by neurons with receptive fields of a portion of visual space, typically in a mutually inhibitory center-surround organization, such that a neuron will receive inputs from other related neurons (Burkhalter & Bernardo, 1989; Carandini & Heeger, 1994; Carandini, Horton, & Sincich, 2007). A very efficient way to accomplish this task is to keep

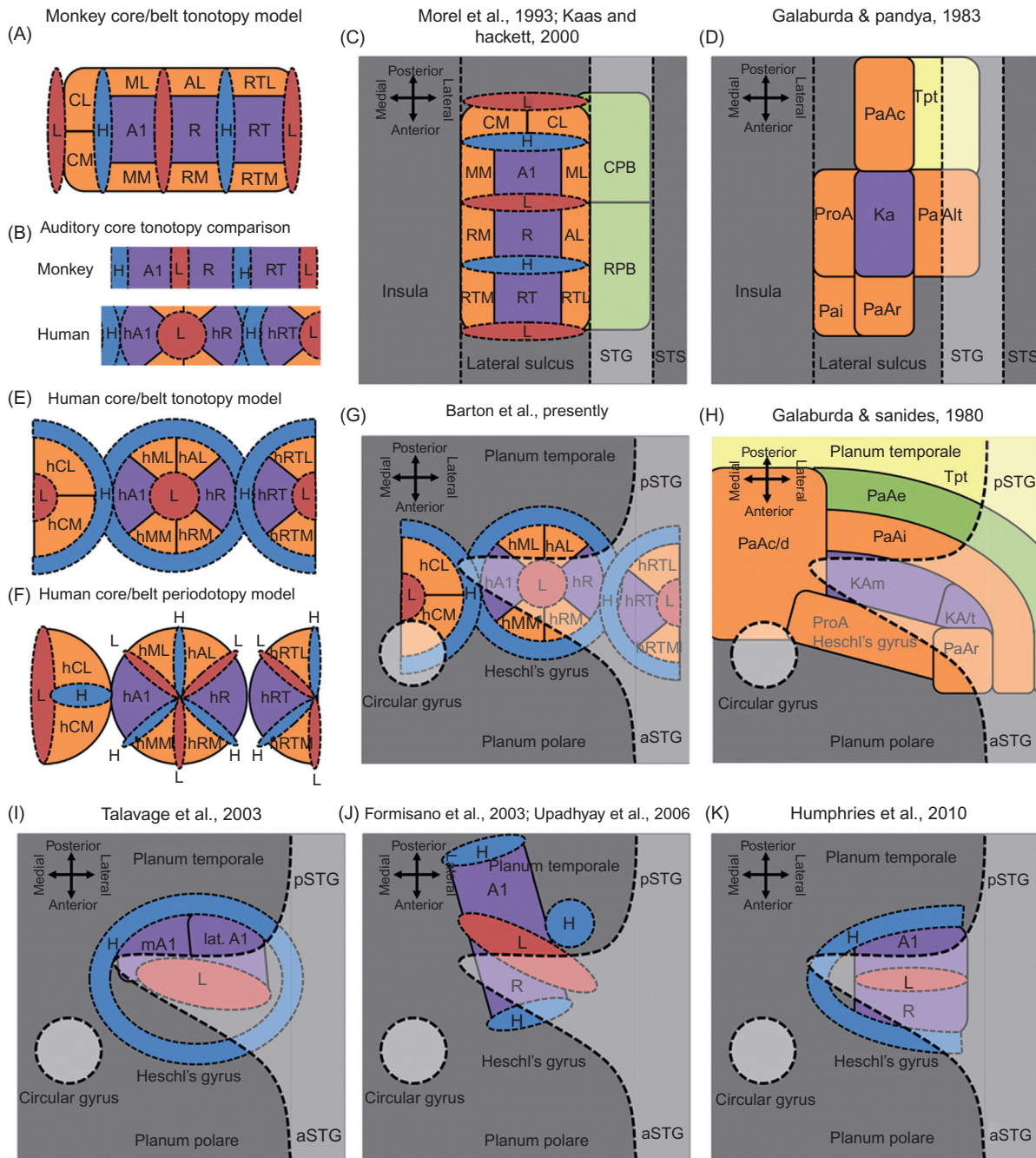


FIGURE 5.3 Comparison of present “clover leaf” cluster organization with human and monkey tonotopic and anatomical data. Cartoon models depict representations of the original models cited above each figure, modified for consistency here. “L” stands for “low” and “H” stands for “high,” referring to low (red regions) or high (blue regions) model tonotopic or periodotopic responses. Dark gray indicates sulci or the plane of the lateral fissure, whereas light gray indicates gyri. Purple regions represent auditory core. Orange regions indicate auditory belt. Green regions indicate auditory parabelt. Yellow regions indicate temporal planum temporal (Tpt). All figures are oriented along the same global axes (see direction legends). (A) Monkey core/belt tonotopy model. (B) Auditory core tonotopy comparison. Top: monkey. Bottom: human. (C) Tonotopic model of monkey auditory core, belt, and parabelt. (D) Cytoarchitectonic model of monkey auditory cortex. (E) Our human core/belt tonotopy model. (F) Our human core/belt periodotopy model. (G) Our tonotopic model of human belt and core. (H) Cytoarchitectonic model of human auditory cortex. (I–K) Recent human fMRI tonotopy models.

neurons that analyze nearby locations in space close to one another (Chklovskii & Koulakov, 2004; Mitchison, 1991; Moradi & Heeger, 2009; Shapley et al., 2007). As a result, visual areas are organized retinotopically; that

is, nearby points of visual space are represented by neurons in nearby locations in cortex after the organization in the retina (Brewer et al., 2005; Wandell, 1999; Wandell et al., 2005, 2007). Because visual space is

basically two-dimensional, we can chart two gradients: eccentricity (i.e., distance from a central fixation point) and polar angle (i.e., angular distance around a central fixation point). A VFM can be defined where these two gradients are measured in the same location of cortex, each representing most or all of one hemifield of visual space and positioned orthogonally to one another.

Retinotopy allows for efficient connections within a VFM, but what about between VFMs? One organizational pattern that would maintain efficient connections between nearby points in space across maps would be to have the representations of a visuospatial gradient reverse from one visual area to the next at the visual area boundaries, such that two VFMs abut at a merged representation of, for example, the upper vertical meridian of the visual field, as seen in the adjoining AFMs elsewhere (Barton et al., 2012; Figure 5.2). To be efficient for two gradient dimensions, an efficient pattern is to have approximately circular clusters of maps. Then, reversals of one dimension occur between maps within the cluster (e.g., polar angle) and reversals for the other occur between maps in different clusters (e.g., eccentricity). The result is concentric rings of increasingly eccentric iso-eccentricity representations expanding from the center of a cluster and lines of isopolar angles extending from the center to the periphery of the cluster like spokes on a wheel. Such clusters of VFMs have been discovered in human and monkey visual cortex and have been termed “clover leaf” clusters (Brewer & Barton, 2011; Kolster, Peeters, & Orban, 2010; Wandell et al., 2005, 2007). For a recent detailed discussion of VFM organization and the implications of “clover leaf” clusters, see Brewer and Barton (2012).

5.8 “CLOVER LEAF” CLUSTERS ACROSS SENSES

Revealing a similar macrostructural organization to the visual system, the first “clover leaf” cluster was discovered in the human auditory system on HG (Barton et al., 2012). The same benefit of efficient connectivity is achieved in the same way, by representing nearby portions of auditory acoustic dimensions (i.e., tonotopy and periodotopy) in nearby portions of cortex. Specifically, the first auditory “clover leaf” cluster consists of six AFMs: hA1, hAL, hML, hR, hRM, and hMM. Concentric circles of increasing iso-tone bands expand from the low-frequency representation centered on HG, with iso-period bands extending from the center to the periphery of the cluster like spokes on a wheel. Abutting the cluster where HG meets the STG, there exists a tonotopic reversal into three additional AFMs: hRT, hRTL, and hRTM. Additionally, two more AFMs abut the HG cluster medially: hCM

and hCL. Although hRT, hRTL, hRTM, hCM, and hCL have not been shown to be organized into complete clusters of AFMs yet, we suspect that they are as well; more research is required to determine whether that is the case.

It is important to consider the monkey cortical model now that the first human auditory “clover leaf” cluster has been discovered. Because tonotopy and cytoarchitecture indicate that the early auditory cortical organization is very similar across these primate species, it is very likely that the monkey areas are organized into “clover leaf” clusters as well. Additionally, “clover leaf” clusters in the visual domain have been found to exist in macaque in homologous areas to clusters in humans (Kolster et al., 2009, 2010), suggesting that the same will be true in the auditory domain. It is impossible to know for certain until orthogonal periodotopic gradients are identified in the same monkey cortex as tonotopic gradients (Barton et al., 2012).

One interesting feature of “clover leaf” clusters is that there must be an even number of maps in a cluster, likely to minimize connection length by always having gradient reversals at the adjoining boundaries between maps. With an odd number of maps in a cluster, there would need to be at least one discrete jump between periodotopic gradient representations, which would reduce the connection efficiency. So far, “clover leaf” clusters have only been observed with even numbers of maps in a cluster (Brewer & Barton, 2012; Kolster et al., 2009, 2010; Wandell et al., 2005, 2007). Another interesting feature is that there need not be the same number of maps in each cluster; so far, two, four, and six maps have been observed in “clover leaf” clusters. Finally, the fact that these clusters of sensory field maps have been observed with such similar characteristics across two senses strongly implies that similar organizational schemes are common for sensory systems in the brain in general.

5.9 CONCLUSION

The cortical organization of the human auditory system so far has been incompletely measured. Although we know some of the features and locations of low-level processing in cortex, until recently we did not have the tools to localize individual AFMs. The key insight to the second dimension of AFMs, periodotopy, was recently discovered. Because tonotopic and periodotopic gradients are represented orthogonally to one another along the cortical surface, it is possible to accurately differentiate the locations of individual cortical AFMs rather than to attempt to estimate map boundaries based only on tonotopy. Additionally, a new

organizational scheme of AFMs has been revealed: the “clover leaf” cluster. With these new insights into AFM organization, researchers can now better localize and identify specific regions of auditory cortex across subjects and more accurately investigate which computations each of the AFMs subserves. Human visual and auditory cortex interestingly share a common organizational scheme, with each sensory system compartmentalized into cortical field maps that are themselves arranged on a larger scale into “clover leaf” clusters. Such similarity may be common across many sensory systems, which may aid in the future identification of cortical field maps in the representation of other senses.

Naturally, many important questions remain unanswered. The AFMs identified so far are unlikely to be the last; novel human cortical VFMs continue to be discovered after two decades of research, and we expect that additional AFMs will be measured in human auditory cortex outside of HG. Because complex language is a uniquely human trait, animal models offer little guidance as to which AFMs to expect to perform relevant computations. However, evidence from monkey perception of monkey vocalizations (Petkov et al., 2008) suggests distinct cortical regions as strong candidates for investigation of specific AFMs subserving human speech perception. Armed with greater knowledge of the inputs to and organization of the initial tiers of the auditory processing hierarchy, researchers will finally be in a position to rigorously investigate the nature of higher-order speech perception computations (Hickok & Poeppel, 2007).

References

- Barton, B., Venezia, J. H., Saberi, K., Hickok, G., & Brewer, A. A. (2012). Orthogonal acoustic dimensions define auditory field maps in human cortex. [Research Support, N.I.H., Extramural Research Support, Non-U.S. Gov't]. *Proceedings of the National Academy of Sciences of the United States of America*, 109(50), 20738–20743. Available from: <http://dx.doi.org/10.1073/pnas.1213381109>.
- Baumann, S., Griffiths, T. D., Sun, L., Petkov, C. I., Thiele, A., & Rees, A. (2011). Orthogonal representation of sound dimensions in the primate midbrain. *Nature Neuroscience*, 14(4), 423–425. Available from: <http://dx.doi.org/10.1038/nn.2771>.
- Brewer, A. A., & Barton, B. (2011). ‘Clover Leaf’ Clusters in Human Visual Cortex. Toulouse, France: European Conference on Visual Perception. Perception 40 (ECP Abstract Supplement), 48.
- Brewer, A. A., & Barton, B. (2012). Visual field map organization in human visual cortex. In S. Molotchnikoff (Ed.), *Visual Cortex*. New York: InTech.
- Brewer, A. A., Liu, J., Wade, A. R., & Wandell, B. A. (2005). Visual field maps and stimulus selectivity in human ventral occipital cortex. *Nature Neuroscience*, 8(8), 1102–1109. Available from: <http://dx.doi.org/10.1038/nn1507>.
- Burkhalter, A., & Bernardo, K. L. (1989). Organization of corticocortical connections in human visual cortex. *Proceedings of the National Academy of Sciences of the United States of America*, 86(3), 1071–1075.
- Carandini, M., & Heeger, D. J. (1994). Summation and division by neurons in primate visual cortex. [Research Support, Non-U.S. Gov't Research Support, U.S. Gov't, Non-P.H.S. Research Support, U.S. Gov't, P.H.S.]. *Science*, 264(5163), 1333–1336.
- Carandini, M., Horton, J. C., & Sincich, L. C. (2007). Thalamic filtering of retinal spike trains by postsynaptic summation. *Journal of Vision*, 7(14), 20, 1–11. Available from: <http://dx.doi.org/10.1167/7.14.20/7/14/20/> [pii].
- Chklovskii, D. B., & Koulakov, A. A. (2004). Maps in the brain: What can we learn from them? *Annual Review of Neuroscience*, 27, 369–392. Available from: <http://dx.doi.org/10.1146/annurev.neuro.27.070203.144226>.
- Dacey, D. M. (2000). Parallel pathways for spectral coding in primate retina. [Research Support, U.S. Gov't, P.H.S. Review]. *Annual Review of Neuroscience*, 23, 743–775. Available from: <http://dx.doi.org/10.1146/annurev.neuro.23.1.743>.
- Da Costa, S., van der Zwaag, W., Marques, J. P., Frackowiak, R. S., Clarke, S., & Saenz, M. (2011). Human primary auditory cortex follows the shape of Heschl's gyrus. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 31(40), 14067–14075. Available from: <http://dx.doi.org/10.1523/JNEUROSCI.2000-11.2011>.
- Dau, T., Kollmeier, B., & Kohlrausch, A. (1997). Modeling auditory processing of amplitude modulation. II. Spectral and temporal integration. *The Journal of the Acoustical Society of America*, 102 (5 Pt 1), 2906–2919.
- de la Mothe, L. A., Blumell, S., Kajikawa, Y., & Hackett, T. A. (2006). Cortical connections of the auditory cortex in marmoset monkeys: Core and medial belt regions. *The Journal of Comparative Neurology*, 496(1), 27–71. Available from: <http://dx.doi.org/10.1002/cne.20923>.
- DeYoe, E. A., Carman, G. J., Bandettini, P., Glickman, S., Wieser, J., Cox, R., et al. (1996). Mapping striate and extrastriate visual areas in human cerebral cortex. [Research Support, U.S. Gov't, P.H.S.]. *Proceedings of the National Academy of Sciences of the United States of America*, 93(6), 2382–2386.
- Dick, F., Tierney, A. T., Lutti, A., Josephs, O., Sereno, M. I., & Weiskopf, N. (2012). *In vivo* functional and myeloarchitectonic mapping of human primary auditory areas. [Research Support, N.I.H., Extramural Research Support, Non-U.S. Gov't]. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 32(46), 16095–16105. Available from: <http://dx.doi.org/10.1523/JNEUROSCI.1712-12.2012>.
- Dougherty, R. F., Koch, V. M., Brewer, A. A., Fischer, B., Modersitzki, J., & Wandell, B. A. (2003). Visual field representations and locations of visual areas V1/2/3 in human visual cortex. *Journal of Vision*, 3(10), 586–598. Available from: <http://dx.doi.org/10.1167/3.10.1/3/10/1/> [pii].
- Ewert, S. D., & Dau, T. (2000). Characterizing frequency selectivity for envelope fluctuations. *The Journal of the Acoustical Society of America*, 108(3 Pt 1), 1181–1196.
- Formisano, E., Kim, D. S., Di Salle, F., van de Moortele, P. F., Ugurbil, K., & Goebel, R. (2003). Mirror-symmetric tonotopic maps in human primary auditory cortex. *Neuron*, 40(4), 859–869. Available from: [http://dx.doi.org/10.1016/s0896-6273\(03\)00669-X](http://dx.doi.org/10.1016/s0896-6273(03)00669-X) [pii].
- Fullerton, B. C., & Pandya, D. N. (2007). Architectonic analysis of the auditory-related areas of the superior temporal region in human brain. *The Journal of Comparative Neurology*, 504(5), 470–498. Available from: <http://dx.doi.org/10.1002/cne.21432>.
- Galaburda, A., & Sanides, F. (1980). Cytoarchitectonic organization of the human auditory cortex. *The Journal of Comparative Neurology*, 190(3), 597–610. Available from: <http://dx.doi.org/10.1002/cne.901900312>.
- Hackett, T. A., Preuss, T. M., & Kaas, J. H. (2001). Architectonic identification of the core region in auditory cortex of macaques, chimpanzees, and humans. *The Journal of Comparative Neurology*,

- 441(3), 197–222. Available from: <http://dx.doi.org/10.1002/cne.1407>.
- Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. [Research Support, N.I.H., Extramural Review]. *Nature Reviews Neuroscience*, 8(5), 393–402. Available from: <http://dx.doi.org/10.1038/nrn2113>.
- Hsieh, I. H., & Saberi, K. (2010). Detection of sinusoidal amplitude modulation in logarithmic frequency sweeps across wide regions of the spectrum. *Hearing Research*, 262(1–2), 9–18. Available from: <http://dx.doi.org/10.1016/j.heares.2010.02.002>.
- Humphries, C., Liebenthal, E., & Binder, J. R. (2010). Tonotopic organization of human auditory cortex. *Neuroimage*, 50(3), 1202–1211. Available from: <http://dx.doi.org/10.1016/j.neuroimage.2010.01.046>.
- Kaas, J. H., & Hackett, T. A. (1998). Subdivisions of auditory cortex and levels of processing in primates. *Audiology and Neuro-Otology*, 3(2–3), 73–85. Available from: <http://dx.doi.org/10.1159/000013783> [pii].
- Kaas, J. H., & Hackett, T. A. (2000). Subdivisions of auditory cortex and processing streams in primates. *Proceedings of the National Academy of Sciences of the United States of America*, 97(22), 11793–11799. Available from: <http://dx.doi.org/10.1073/pnas.97.22.1179397/22/11793> [pii].
- Kolster, H., Mandeville, J. B., Arsenault, J. T., Ekstrom, L. B., Wald, L. L., & Vanduffel, W. (2009). Visual field map clusters in macaque extrastriate visual cortex. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 29(21), 7031–7039. Available from: <http://dx.doi.org/10.1523/JNEUROSCI.0518-09.2009>.
- Kolster, H., Peeters, R., & Orban, G. A. (2010). The retinotopic organization of the human middle temporal area MT/V5 and its cortical neighbors. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 30(29), 9801–9820. Available from: <http://dx.doi.org/10.1523/JNEUROSCI.2069-10.2010>.
- Krubitzer, L. (2007). The magnificent compromise: Cortical field evolution in mammals. *Neuron*, 56(2), 201–208. Available from: <http://dx.doi.org/10.1016/j.neuron.2007.10.002>.
- Kumar, S., & Hedges, S. B. (1998). A molecular timescale for vertebrate evolution. [Research Support, U.S. Gov't, Non-P.H.S. Research Support, U.S. Gov't, P.H.S.]. *Nature*, 392(6679), 917–920. Available from: <http://dx.doi.org/10.1038/31927>.
- Kusmirek, P., & Rauschecker, J. P. (2009). Functional specialization of medial auditory belt cortex in the alert rhesus monkey. [Research Support, N.I.H., Extramural]. *Journal of Neurophysiology*, 102(3), 1606–1622. Available from: <http://dx.doi.org/10.1152/jn.00167.2009>.
- Langner, G., Dinse, H. R., & Godde, B. (2009). A map of periodicity orthogonal to frequency representation in the cat auditory cortex. *Frontiers in Integrative Neuroscience*, 3, 27. Available from: <http://dx.doi.org/10.3389/fnint.2009.07.027>.
- McBeath, M. K., & Neuhoff, J. G. (2002). The Doppler effect is not what you think it is: Dramatic pitch change due to dynamic intensity change. [Research Support, Non-U.S. Gov't Research Support, U.S. Gov't, Non-P.H.S.]. *Psychonomic Bulletin & Review*, 9(2), 306–313.
- Menon, V., Levitin, D. J., Smith, B. K., Lembke, A., Krasnow, B. D., Glazer, D., et al. (2002). Neural correlates of timbre change in harmonic sounds. [Research Support, Non-U.S. Gov't Research Support, U.S. Gov't, P.H.S.]. *Neuroimage*, 17(4), 1742–1754.
- Merzenich, M. M., & Brugge, J. F. (1973). Representation of the cochlear partition of the superior temporal plane of the macaque monkey. *Brain Research*, 50(2), 275–296.
- Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. [Research Support, Non-U.S. Gov't Research Support, U.S. Gov't, Non-P.H.S. Research Support, U.S. Gov't, P.H.S. Review]. *Annual Review of Psychology*, 42, 135–159. Available from: <http://dx.doi.org/10.1146/annurev.ps.42.020191.001031>.
- Mitchison, G. (1991). Neuronal branching patterns and the economy of cortical wiring. *Proceedings Biological Sciences/The Royal Society*, 245(1313), 151–158. Available from: <http://dx.doi.org/10.1098/rspb.1991.0102>.
- Moradi, F., & Heeger, D. J. (2009). Inter-ocular contrast normalization in human visual cortex. *Journal of Vision*, 9(3), 13 11-22. Available from: <http://dx.doi.org/10.1167/9.3.13/9/3/13/> [pii].
- Morel, A., Garraghty, P. E., & Kaas, J. H. (1993). Tonotopic organization, architectonic fields, and connections of auditory cortex in macaque monkeys. *The Journal of Comparative Neurology*, 335(3), 437–459. Available from: <http://dx.doi.org/10.1002/cne.903350312>.
- Petkov, C. I., Kayser, C., Augath, M., & Logothetis, N. K. (2006). Functional imaging reveals numerous fields in the monkey auditory cortex. *PLoS Biology*, 4(7), e215. Available from: <http://dx.doi.org/10.1371/journal.pbio.0040215>.
- Petkov, C. I., Kayser, C., Augath, M., & Logothetis, N. K. (2009). Optimizing the imaging of the monkey auditory cortex: Sparse vs. continuous fMRI. *Magnetic Resonance Imaging*, 27(8), 1065–1073. Available from: <http://dx.doi.org/10.1016/j.mri.2009.01.018>.
- Petkov, C. I., Kayser, C., Steudel, T., Whittingstall, K., Augath, M., & Logothetis, N. K. (2008). A voice region in the monkey brain. [Research Support, Non-U.S. Gov't]. *Nature Neuroscience*, 11(3), 367–374. Available from: <http://dx.doi.org/10.1038/nn2043>.
- Poeppel, D., Emmorey, K., Hickok, G., & Pylkkanen, L. (2012). Towards a new neurobiology of language. [Research Support, N.I.H., Extramural Research Support, U.S. Gov't, Non-P.H.S. Review]. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 32(41), 14125–14131. Available from: <http://dx.doi.org/10.1523/JNEUROSCI.3244-12.2012>.
- Press, W. A., Brewer, A. A., Dougherty, R. F., Wade, A. R., & Wandell, B. A. (2001). Visual areas and spatial summation in human visual cortex. *Vision Research*, 41(10-11), 1321–1332. Available from: [http://dx.doi.org/10.1016/S0042-6989\(01\)00074-8](http://dx.doi.org/10.1016/S0042-6989(01)00074-8).
- Rauschecker, J. P., & Scott, S. K. (2009). Maps and streams in the auditory cortex: Nonhuman primates illuminate human speech processing. [Research Support, N.I.H., Extramural Research Support, Non-U.S. Gov't Research Support, U.S. Gov't, Non-P.H.S. Review]. *Nature Neuroscience*, 12(6), 718–724. Available from: <http://dx.doi.org/10.1038/nn.2331>.
- Rauschecker, J. P., & Tian, B. (2004). Processing of band-passed noise in the lateral auditory belt cortex of the rhesus monkey. [Research Support, U.S. Gov't, P.H.S.]. *Journal of Neurophysiology*, 91(6), 2578–2589. Available from: <http://dx.doi.org/10.1152/jn.00834.2003>.
- Ress, D., & Chandrasekaran, B. (2013). Tonotopic organization in the depth of human inferior colliculus. *Frontiers in Integrative Neuroscience*, 7, 586. Available from: <http://dx.doi.org/10.3389/fnint.2013.00586>.
- Rivier, F., & Clarke, S. (1997). Cytochrome oxidase, acetylcholinesterase, and NADPH-diaphorase staining in human supratemporal and insular cortex: Evidence for multiple auditory areas. *Neuroimage*, 6(4), 288–304. Available from: <http://dx.doi.org/10.1006/nimg.1997.0304>.
- Saenz, M., & Langers, D. R. (2014). Tonotopic mapping of human auditory cortex. [Review]. *Hearing Research*, 307, 42–52. Available from: <http://dx.doi.org/10.1016/j.heares.2013.07.016>.
- Schreiner, C. E., & Winer, J. A. (2007). Auditory cortex mapping: Principles, projections, and plasticity. [Research Support, N.I.H., Extramural Review]. *Neuron*, 56(2), 356–365. Available from: <http://dx.doi.org/10.1016/j.neuron.2007.10.013>.
- Sereno, M. I., Dale, A. M., Reppas, J. B., Kwong, K. K., Belliveau, J. W., Brady, T. J., et al. (1995). Borders of multiple visual areas in humans revealed by functional magnetic resonance imaging. [Research Support, Non-U.S. Gov't Research Support, U.S. Gov't, P.H.S.]. *Science*, 268(5212), 889–893.
- Shapley, R., Hawken, M., & Xing, D. (2007). The dynamics of visual responses in the primary visual cortex. *Progress in Brain Research*,

- 165, 21–32. Available from: [http://dx.doi.org/10.1016/S0079-6123\(06\)65003-6](http://dx.doi.org/10.1016/S0079-6123(06)65003-6).
- Spoendlin, H. (1979). Sensory neural organization of the cochlea. [Review]. *The Journal of Laryngology and Otology*, 93(9), 853–877.
- Sweet, R. A., Dorph-Petersen, K. A., & Lewis, D. A. (2005). Mapping auditory core, lateral belt, and parabelt cortices in the human superior temporal gyrus. *The Journal of Comparative Neurology*, 491(3), 270–289. Available from: <http://dx.doi.org/10.1002/cne.20702>.
- Talavage, T. M., Sereno, M. I., Melcher, J. R., Ledden, P. J., Rosen, B. R., & Dale, A. M. (2004). Tonotopic organization in human auditory cortex revealed by progressions of frequency sensitivity. *Journal of Neurophysiology*, 91(3), 1282–1296. Available from: <http://dx.doi.org/10.1152/jn.01125.200201125.2002> [pii].
- Tanji, K., Leopold, D. A., Ye, F. Q., Zhu, C., Malloy, M., Saunders, R. C., et al. (2010). Effect of sound intensity on tonotopic fMRI maps in the unanesthetized monkey. *Neuroimage*, 49(1), 150–157. Available from: <http://dx.doi.org/10.1016/j.neuroimage.2009.07.029>.
- Tian, B., & Rauschecker, J. P. (2004). Processing of frequency-modulated sounds in the lateral auditory belt cortex of the rhesus monkey. [Research Support, U.S. Gov't, P.H.S.]. *Journal of Neurophysiology*, 92(5), 2993–3013. Available from: <http://dx.doi.org/10.1152/jn.00472.2003>.
- Upadhyay, J., Ducros, M., Knaus, T. A., Lindgren, K. A., Silver, A., Tager-Flusberg, H., et al. (2007). Function and connectivity in human primary auditory cortex: A combined fMRI and DTI study at 3 Tesla. *Cerebral Cortex*, 17(10), 2420–2432. Available from: <http://dx.doi.org/10.1093/cercor/bhl150>.
- Van Essen, D. C., Felleman, D. J., DeYoe, E. A., Olavarria, J., & Knierim, J. (1990). Modular and hierarchical organization of extrastriate visual cortex in the macaque monkey. *Cold Spring Harbor Symposia on Quantitative Biology*, 55, 679–696.
- Wandell, B. A. (1999). Computational neuroimaging of human visual cortex. *Annual Review of Neuroscience*, 22, 145–173. Available from: <http://dx.doi.org/10.1146/annurev.neuro.22.1.145>.
- Wandell, B. A., Brewer, A. A., & Dougherty, R. F. (2005). Visual field map clusters in human cortex. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences*, 360(1456), 693–707. Available from: <http://dx.doi.org/10.1098/rstb.2005.1628>.
- Wandell, B. A., Dumoulin, S. O., & Brewer, A. A. (2007). Visual field maps in human cortex. *Neuron*, 56(2), 366–383. Available from: <http://dx.doi.org/10.1016/j.neuron.2007.10.012>.
- Woods, D. L., Herron, T. J., Cate, A. D., Yund, E. W., Stecker, G. C., Rinne, T., et al. (2010). Functional properties of human auditory cortical fields. *Frontiers in Systems Neuroscience*, 4, 155. Available from: <http://dx.doi.org/10.3389/fnsys.2010.00155>.
- Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: Music and speech. *Trends in Cognitive Sciences*, 6(1), 37–46.