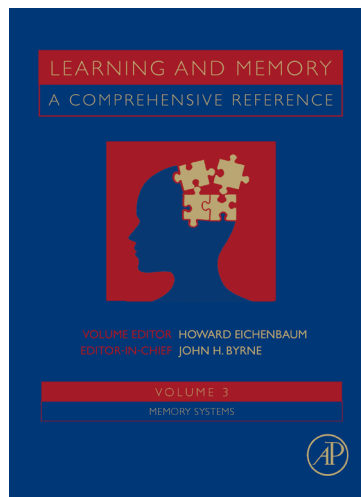


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R. Mooney, J. Prather, and T. Roberts. Neurophysiology of Birdsong Learning.
In H. Eichenbaum (Ed.), Memory Systems. Vol. [3] of Learning and Memory:
A Comprehensive Reference, 4 vols.
(J.Byrne Editor), pp. [441-474] Oxford: Elsevier.

3.23 Neurophysiology of Birdsong Learning

R. Mooney, J. Prather and T. Roberts, Duke University, Durham, NC, USA

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3.23.1 Synopsis

Songbirds are one of the few nonhuman animals that learn to vocalize. Juvenile songbirds first memorize a tutor song and then match this memorized model using auditory feedback. The close parallels between song learning in birds and speech learning in humans have piqued interest in the mechanisms of song learning. The neurobiological analysis of birdsong was revolutionized by the discovery of a specialized constellation of brain nuclei necessary to singing. Part of this ‘song system’ includes a basal ganglia pathway necessary to song plasticity, providing an important insight into neural mechanisms of song learning. Other important issues, such as where tutor song memories are stored and how and where auditory feedback registers in the brain of the singing bird, are now beginning to be addressed, with many of the most exciting results about to unfold. This chapter discusses song’s function as a communication signal, the role experience plays in song development, peripheral and central song mechanisms, and neural mechanisms of song learning. See Chapter 1.17 for additional discussion of bird song learning.

3.23.2 The Song Behavior

3.23.2.1 Taxonomy of Songbirds

Oscine songbirds (Aves, Passeriformes, Oscini) comprise over half of the approximately 8000 extant avian species. Oscine songbirds learn to sing, which distinguishes them from most other birds – and indeed almost all nonhuman animals. Most neurobiological

studies of singing and song learning have focused on a few domesticated or partially domesticated songbirds that breed readily in captivity. These include zebra finches (*Taeniopygia guttata*), a colonial and nomadic species native to the Australian Outback, Society finches (*Lonchura domestica*), which have been fully domesticated for centuries, and canaries (*Serinus canaria*), a seasonally breeding cardueline finch native to the Canary Islands (Figure 1). Although these species will continue to be useful, the great diversity of singing-related behaviors in other wild songbirds provides a vast and currently underexploited resource for comparative analysis of song learning mechanisms.

3.23.2.2 Calls versus Songs

Birds utter both calls and songs (Marler, 2004b; Williams, 2004). Calls are brief sounds (~100 ms) with relatively simple acoustic structure. Songs are longer in duration (typically 1–3 s) and typically more complex in structure, often consisting of extensive and rapid frequency and amplitude modulations. Song complexity does not always reflect learning: The songs of some suboscine birds (Aves, Passeriformes, Tyranni) are complex but innate. Moreover, although calls are simpler than songs, some fine acoustical features of calls also may be learned.

3.23.2.3 Song Nomenclature

Songs can be visualized with a sonogram, which plots frequency as a function of time (Figure 1). The smallest song unit is the note, a short burst of sound (~5–100 ms) that is separated by brief (5–10 ms) silence and that appears as a continuous trace on a

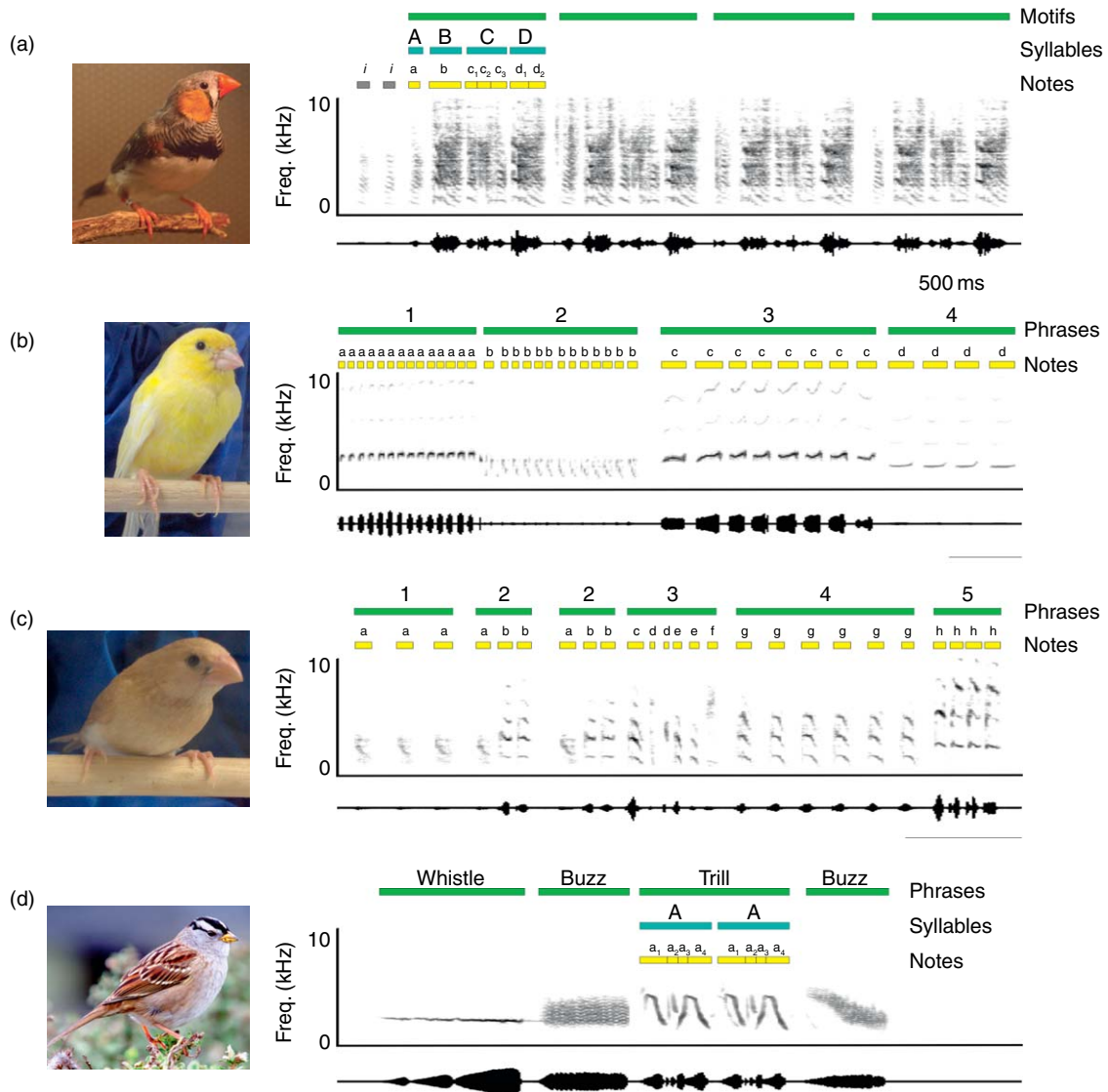


Figure 1 Four male songbirds and their crystallized songs, depicted by an oscillogram (bottom) and a sonogram (top). Colored boxes above each sonogram delineate song components for each exemplar. (a) Zebra finch (*Taeniopygia guttata*) song bouts begin with a series of brief introductory notes (denoted by 'i' and gray boxes) followed by one or more identical motifs (green boxes). Each motif consists of a stereotyped sequence of syllables (blue boxes), with each syllable comprising one or a few notes (yellow boxes). (b) Canary (*Serinus canaria*) song consists of a series of phrases (green boxes), each of which consists of a trilled single-note (yellow boxes) or multinote syllable (not shown). Male canaries can sing a large number of different phrases, which can be combined in different sequences to produce a large repertoire of songs. (c) Society finch (*Lonchura domestica*) song is characterized by phrases (green boxes) consisting of a sequence of notes or syllables (yellow boxes). Although the note sequence that defines each phrase is typically stereotyped, the phrase sequence can vary across song bouts. (d) White-crowned sparrow (*Zonotrichia leucophrys*) song begins with a whistle phrase (green boxes) a combination of other phrases referred to as buzzes and syllables (a repeated sequence of one or more notes). Zebra finch image courtesy Daniel D. Baleckaitis, canary and bengalese finch images courtesy of David Kloetzer and Jon Prather, white-crowned sparrow image courtesy Vladimir Pravosudov (University of Nevada Reno).

sonogram. One or more notes are grouped to form syllables, which are arranged in specific sequences known as motifs, phrases, or songs, depending on the species (Figure 1) (Marler, 2004a). In those birds that

produce several distinct songs, each song is referred to as a song type. Song typically lasts ~2 s, but it can be as long as 30 s in canaries and European starlings. Songs are uttered one to several times in quick

succession to form a bout, which can be separated from the next bout by many seconds or even minutes.

3.23.2.4 Function of Song as Communication Signal

3.23.2.4.1 Territorial defense

In most songbirds, song is produced by males, primarily during breeding season. Song serves two primary functions: territorial defense and mate attraction (Catchpole and Slater, 1995). Song's role in territorial defense can be shown by poking a small hole in one of the air sacs in the bird's specialized respiratory system. Such air sac rupture temporarily mutes the bird, and he quickly loses his territory to neighboring males (McDonald, 1989). In a similar vein, neighboring males are reluctant to invade territory vacated by a fellow conspecific bird if the absent male's songs are played through speakers positioned in the vacant territory (Krebs, 1977). Thus, song is necessary to enable a bird to defend his territory against other males and can even serve this function in the absence of visual displays or physical combat.

Distinguishing neighbors from strangers also is important to territorial defense. During the breeding season, a male will aggressively approach and even attack speakers broadcasting unfamiliar songs (Catchpole and Slater, 1995). These territorial displays habituate when the male is repeatedly exposed to several 'virtual neighbors' simulated by songs played through separate speakers. However, when the male hears a 'new' bird's song through one of the speakers, he again attacks, indicating he detected a stranger's song on a background of familiar songs (Nelson and Marler, 1989).

3.23.2.4.2 Mate attraction and female song preferences

The other major function of male song is to attract and arouse conspecific females. Song is a powerful acoustic aphrodisiac that can draw in females literally from out of sight. Song's arousing qualities can be revealed by simply playing it through a loudspeaker. For conspecific female birds in breeding condition, this acoustical stimulation is sufficient to evoke a lordotic response, known as a copulation solicitation display (CSD).

The CSD has helped reveal song features females find attractive. Females tend to favor longer songs containing more complex syllables (Clayton and Prove, 1989), features that distinguish learned songs from those produced by untutored birds (Searcy et al.,

1985). Moreover, females prefer the highly stereotyped (crystallized) songs of adult males in breeding condition. In swamp sparrows, females favor songs most challenging for males to produce (Ballentine et al., 2004). Finally, although females often do not sing, their capacity for song discrimination can surpass that of males. For example, female redwing blackbirds make CSDs to the songs of a male conspecific but not to a mockingbird's imitations of this song, while male redwing blackbirds attack speakers broadcasting either song (Searcy and Brenowitz, 1988).

From an evolutionary perspective, female songbirds select males partly based on learned features of song (Searcy et al., 1985). Consequently, sexual selection in songbirds has exerted extraordinary selective pressure on brain structures specialized for singing and song learning. As discussed in greater detail later in this chapter, the elaboration of specialized neural circuits for song has proven to be a great boon to neurobiologists interested in vocal learning mechanisms.

3.23.2.5 Acoustic Features of Song Vary with Function and Context

3.23.2.5.1 Broadcast versus local songs

A basic distinction can be made between broadcast songs, which are highly tonal and typically produced by territorial songbirds to propagate over large distances, and local songs intended for a more intimate audience (Figure 1). The acoustic energy in broadcast songs is focused in a narrow-frequency band centered at ~3–4 kHz, avoiding interference with lower-frequency environmental sounds. When broadcast songs propagate over long distances, their tones become 'blurred.' Males disregard spectrally blurred songs, even when played at sound pressure levels approximating songs of nearby birds, indicating that the degree of spectral blurring, rather than absolute loudness, is used to estimate the singer's distance (Naguib and Wiley, 2001). In contrast to broadcast songs, the songs of birds that sing only for a local audience, such as male zebra finches, often are broadband signals that propagate only several to a few tens of meters (Figure 1).

3.23.2.5.2 The importance of social context

Song can vary with social context. The songs of adult male zebra finches directed to another individual are slightly more stereotyped than undirected songs

(Kao and Brainard, 2006). The functional significance of these context-dependent changes is unclear, but activity in the male's brain changes depending on whether he is singing directed or undirected songs (Jarvis et al., 1998; Hessler and Doupe, 1999b). Duetting songbirds also afford another example of social contributions to song structure. In some tropical wrens (*Thryothorus spp.*), both males and females sing a small repertoire of song types, and breeding partners sing precisely coordinated duets thought to facilitate breeding synchrony in their equatorial environment (Langmore, 1998).

3.23.3 Song Learning

3.23.3.1 General Themes

Songbirds learn to sing during a juvenile sensitive period comprising two distinct phases, both dependent on auditory experience (Figures 2 and 3). During the

first phase, known as sensory acquisition, the young bird listens to and memorizes one or more tutor songs. During the ensuing phase of sensorimotor learning, the pupil relies on auditory feedback to match its song to the memorized model. Song crystallization, wherein the song becomes highly stereotyped and usually much less dependent on auditory feedback, signals the end of sensorimotor learning.

In seasonally breeding songbirds that populate temperate regions, 6–10 months separate sensory acquisition and sensorimotor learning (Figure 2). In contrast, these periods overlap in species such as the zebra finch, which crystallize their songs only 3 months after hatching (Figure 2). Regardless of the pace of song learning, young birds evince sensory plasticity, by memorizing one or more tutor songs, and motor plasticity, by vocally imitating one or more song model.

The great diversity of songbird species is paralleled by minor variations on these major song

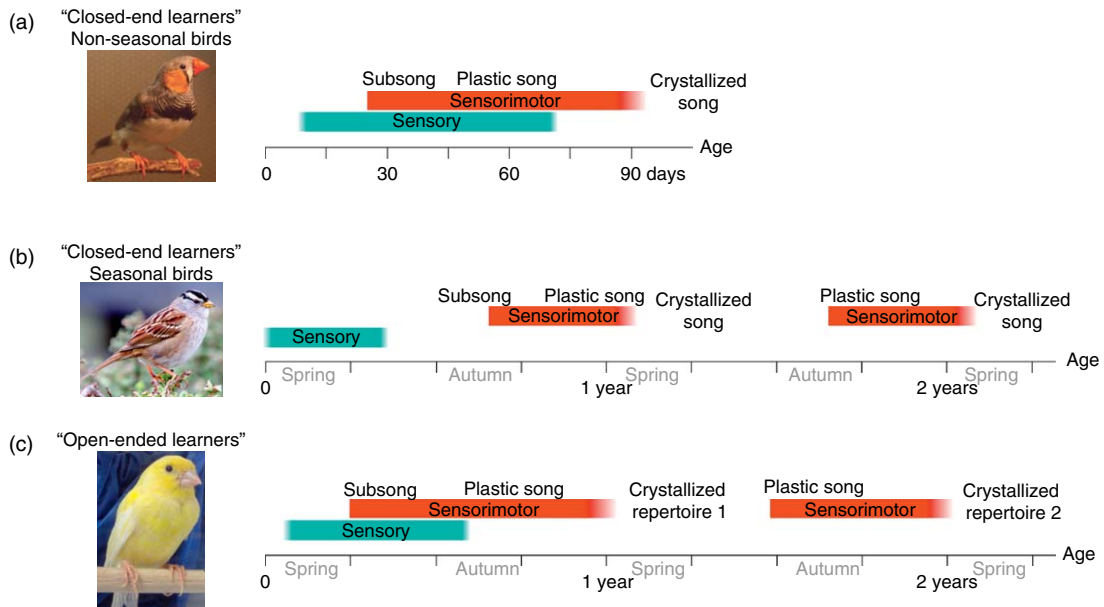


Figure 2 Developmental timelines of song learning in different songbird species illustrate similarities and variations in the song learning process. During sensory acquisition (blue box), the juvenile bird listens to and memorizes one or more tutor songs. During sensorimotor learning (red box), the juvenile matches its own song to the memorized model using auditory feedback. Song crystallization marks the end of sensorimotor learning. 'Closed-end learners,' such as the zebra finch and white-crowned sparrow (a and b), retain the same crystallized song repertoire throughout adulthood, while in 'open-ended learners,' such as the canary, the crystallized repertoire can change from one year to the next. (a) In the zebra finch, the sensory (blue box) and sensorimotor periods (red box) overlap extensively, and song crystallization is complete between 90 and 120 days after hatching. (b) In the white-crowned sparrow, sensory acquisition and sensorimotor learning are separated by many months, indicating that the tutor songs are stored in memory without rehearsal. Song crystallization occurs in the spring, at the end of the first year. Early each ensuing spring, adult male white-crowned sparrows again sing plastic songs, but they recrystallize the same song type as that crystallized in their first year. (c) Canaries are seasonally breeding birds, like white-crowned sparrows, but can exhibit changes in their repertoire of crystallized songs from one year to the next. Zebra finch image courtesy of Daniel D. Baleckaitis, white-crowned sparrow image courtesy of Vladimir Pravosudov (University of Nevada Reno), canary image courtesy of David Klotzner and Jon Prather.

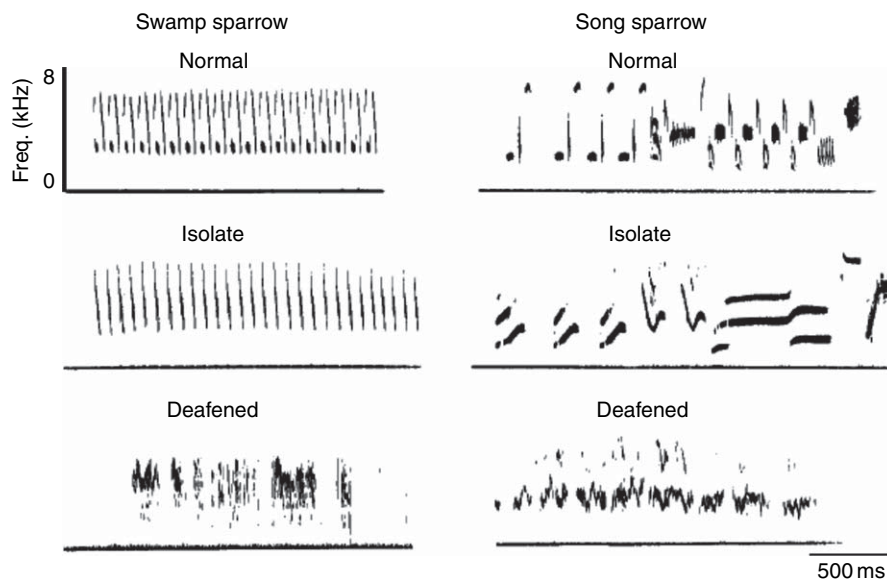


Figure 3 Development of species-typical song structure requires auditory experience of an appropriate song model and experience of singing-related auditory feedback. These sonograms depict songs of adult swamp (left) or song (right) sparrows raised with normal experience of a tutor and with their hearing intact (top row), raised in isolation from other birds' songs with hearing intact (middle) and raised with experience of a tutor song but deafened before sensorimotor learning (bottom). Isolate songs display rudimentary species-typical song features but lack the acoustical complexity of normal wild-type song, underscoring the important role of auditory experience of the tutor song. Songs of deafened birds lack even the rudimentary features of the isolate song, revealing the important role auditory feedback plays in sensorimotor learning. Reprinted from Marler P and Doupe AJ (2000) Singing in the brain. *Proc. Natl. Acad. Sci. USA* 97: 2965–2967. Copyright (2000) National Academy of Sciences, U.S.A, with permission.

learning themes (Figure 2). 'Closed-ended' learners, which include the white-crowned sparrow and the zebra finch, retain one crystallized song throughout adult life. 'Open-ended' learners, such as the canary, continue to modify their songs as adults, although whether such adult plasticity involves copying of new tutor songs remains uncertain.

3.23.3.2 Sensory Acquisition

3.23.3.2.1 Cross-fostering and isolates

Several lines of evidence show that songbirds learn to sing. First, young songbirds transplanted into the nest of another species develop songs resembling those of their foster parents (Immelmann, 1969; Baptista and Petrinovich, 1984, 1986). Second, local song dialects distinguish different breeding populations of the same songbird species (Marler and Tamura, 1964). Third, birds raised without a tutor subsequently fail to sing species-typical songs and, instead, produce rudimentary 'isolate' songs (Figure 3) (Thorpe, 1954, 1958; Immelmann, 1969; Marler, 1970; Price, 1979). This dependence on auditory instruction distinguishes

birdsong from most other animal vocalizations that, regardless of their acoustical complexity, develop through innate processes (Konishi and Nottebohm, 1969; Kroodsma and Konishi, 1991).

3.23.3.2.2 Sensory acquisition: born to learn

Young songbirds are prodigious song mnemonists. The number of models that may be memorized during sensory acquisition can range into the hundreds in some species, and the total exposure required for accurate recall can be remarkably limited. In perhaps the most impressive example of this learning capacity, young nightingales accurately learn 10–20 song types (comprising a total of 75–100 syllables) after hearing them fewer than only 20 times (Hultsch and Todt, 1989a,b). Moreover, these memories are stored for many months before the bird actually begins to sing. This astounding feat of auditory memory is reminiscent of other forms of sensory imprinting and suggests that the juvenile songbird is predisposed to memorize certain sounds almost effortlessly.

Cross-fostering experiments show that juvenile songbirds are flexible in the range of songs they will memorize and subsequently copy (Immelmann, 1969; Baptista and Petrinovich, 1984, 1986). Nonetheless, they prefer to learn conspecific songs when given the opportunity. After being tutored on a recorded medley of conspecific and heterospecific songs, juvenile swamp and song sparrows preferentially copy their conspecific songs (Marler and Peters, 1987, 1989; Marler, 1990). Interestingly, these experiments used recorded tutor songs, indicating that juveniles must innately recognize acoustic cues present in the conspecific songs. In the wild, such innate recognition of conspecific song may help naïve juveniles avoid spurious imprinting on heterospecific songs.

3.23.3.2.3 A sensitive period for sensory acquisition

Sensory acquisition closes between the end of the second and third month after hatching in many species (Figure 2) (Thorpe, 1958; Immelmann, 1969; Marler and Peters, 1987, 1988). Young birds typically fledge at the end of the first month, so in natural settings juveniles socialize with other potential tutors in addition to their fathers. The timing of sensory acquisition has been mapped most precisely in zebra finches, where juveniles were initially raised with tutors, then removed to an isolated environment at various ages (Bohner, 1990). These controlled tutoring experiments suggest that much of what will be copied can be memorized by the end of the fifth week. Complementary experiments in which birds were sequentially exposed to a series of tutors show that juvenile birds become refractory to further copying from new tutors by about the end of the second month (Eales, 1985). The closure of sensory acquisition is not strictly age limited, because raising birds in isolation extends sensory acquisition 1 to 2 months (Eales, 1987; Morrison and Nottebohm, 1993). Nevertheless, birds subjected to late tutoring copy less extensively than do normally tutored birds, and eventually individuals become totally resistant to learning from a tutor.

3.23.3.2.4 Sensory acquisition results in long-lasting memories of the tutor song

A remarkable feature of sensory acquisition is that the memory of the tutor song can be stored for long periods prior to the first attempts at vocal imitation. In seasonally breeding species, such as swamp and song sparrows, imprinting on the tutor song occurs in the late spring immediately after hatching, but the earliest attempts at vocal imitation do not begin until

early in the following spring, a full 8 to 10 months later (Figure 2) (Marler and Peters, 1981, 1982b). This capacity to store the tutor song memory for a long period prior to imitation is especially impressive and is one way in which songbirds may differ from humans, where auditory experience of the vocal model and attempts at vocal imitation overlap.

Long-term storage of the tutor song memory may be a general feature of song learning. Despite their normally compressed song learning schedules, juvenile zebra finches briefly exposed to a tutor, then prevented from hearing their own songs for several months by exposing them to a loud masking noise, imitate the tutor song when the noise is turned off (Funabiki and Konishi, 2003). The long delays between tutor song imprinting and subsequent vocal recall afford an opportunity to search for neural correlates of long-lasting auditory memories.

3.23.3.3 Sensorimotor Learning

3.23.3.3.1 General themes including the role of auditory feedback

During sensorimotor learning, the juvenile matches its own song to the memorized tutor model (Figures 3 and 4). Although sensorimotor learning typically occurs without ongoing exposure to the tutor, pioneering studies by Mark Konishi showed that juvenile birds deafened after sensory acquisition but before or during sensorimotor learning subsequently developed highly abnormal songs (Figure 3) (Konishi, 1965). This observation supports the idea that the juvenile uses auditory feedback to evaluate differences between its own song and a 'template' initially created upon hearing the tutor. Interestingly, Konishi also discovered that birds raised without tutors also develop highly abnormal songs following juvenile deafening (Konishi, 1965). Apparently, even isolate birds use auditory feedback to match their rudimentary songs to an innate 'template.'

Sensorimotor learning comprises several stages (Figure 4) (Immelmann, 1969; Marler and Peters, 1982a). Subsong, which constitutes the young bird's earliest song efforts, is a soft and rambling vocalization with little resemblance to the species-typical song. Subsequently, birds produce plastic songs, which contain recognizable notes and syllables that vary in their acoustical structure and sequence from one bout to the next. This bout-to-bout variability is thought to facilitate exploration of the vocal-acoustic space, enabling the pupil to better match the tutor song. In distinction from sensory acquisition, sensorimotor

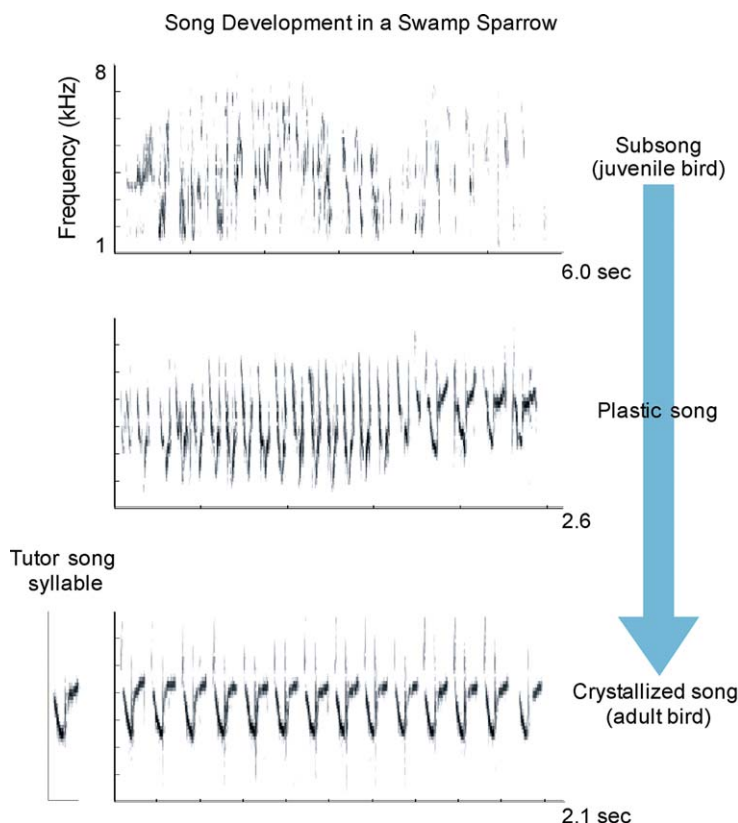


Figure 4 During sensorimotor learning, song progresses from a string of sounds with little recognizable structure ('subsong') to the stereotyped species-typical pattern characteristic of crystallized song. These sonograms depict sensorimotor learning in a male swamp sparrow, a species that in adulthood produces several distinct song types, each consisting of a monosyllabic trill. Subsong contains a variable sequence of notes that bear no obvious resemblance to the tutor song. 'Plastic song' is defined by acoustic features typical of adult song, in this case a trilled syllable similar to one of the tutor songs, and variability in the structure and sequence of notes and syllables. Upon crystallization, the structure and sequence of syllables becomes highly stereotyped. Image created from swamp sparrow data provided by Susan Peters.

learning is a slow process. Over many weeks and tens or hundreds of thousands of vocal renditions, the juvenile's song undergoes plastic changes that render it similar to the tutor model. Thus, juvenile songs display acute variability and adaptive plasticity. Juvenile birds also generate improvised notes and make mistakes in memorization and/or imitation of the tutor song, with the result that their imitations, though highly accurate, are not perfect copies of the tutor. Innate mechanisms also can play a role: juvenile white-crowned sparrows tutored only on overlapping syllable pairs eventually 'stitch' these syllables together to form a complete song phrase (Rose et al., 2004). This interplay between imitation, improvisation, innate constraints, and error yields songs that are unique yet still species typical.

With the onset of sexual maturity, the structure and sequence of notes and syllables becomes highly stereotyped, or 'crystallized.' In contrast to the slow

pace of sensorimotor learning, crystallization can occur very rapidly, often in less than 1 week. In many seasonally breeding songbirds, the male sex hormone testosterone is thought to be the catalyst for crystallization (Marler et al., 1988). Because testosterone levels can fluctuate with changes in day length, adult males of seasonally breeding species sing plastic songs early each spring and then recrystallize their songs as spring days lengthen.

3.23.3.3.2 Syllable overproduction and attrition during sensorimotor learning

Much of what we know about sensorimotor learning stems from studying sparrows, songbirds that breed seasonally and that display an 8-month gap between sensory acquisition and the first stages of plastic song. Syllable overproduction and subsequent attrition are major features of sensorimotor learning in these birds

(Marler and Peters, 1982c). In contrast to crystallized songs, plastic songs in sparrows are not only more variable but also contain a wider range of material, much of it learned from various tutors during sensory acquisition. Thus, the juvenile's plastic songs effectively report the numerous tutor songs stored in memory. Upon crystallization, much of this learned material is deleted, with the consequence that the adult crystallized repertoire represents only a subset of what was actually learned.

3.23.3.3.3 Selection-based models of sensorimotor learning

The sequence of syllable overproduction followed by attrition supports a selection-based model of sensorimotor learning (Marler and Peters, 1982c). In this model, overproduction provides a palette of songs from which the young adult chooses its crystallized repertoire. But is this 'choice' random or instead guided by an instructive process? One idea is that slight variations in late plastic songs help the juvenile gain breeding territory by providing it with the necessary behavioral flexibility to match the dialect of the older, more established breeding males in the neighborhood. Indeed, juvenile white-crowned sparrows crystallize a plastic song most like a white-crowned sparrow song broadcast to them repeatedly through a speaker and delete their other plastic songs (Nelson and Marler, 1994).

3.23.3.3.4 A fine time-scale analysis of sensorimotor learning

The pioneering studies of sensorimotor learning relied on tape recordings, which were scanned by human listeners in real time, limiting the numbers of songs that could be analyzed. The advent of cheap mass storage devices coupled with the development of automated song analysis methods, especially those developed by Ofer Tchernichovski and his coworkers, have provided a blow-by-blow account of sensorimotor learning in zebra finches (Tchernichovski et al., 2000, 2001; Deregnacourt et al., 2005). Such comprehensive analyses have yielded several important insights into vocal learning strategies (Deregnacourt et al., 2005). First, the match between the pupil's song and the tutor model varies systematically over the course of the day, being poorest in the morning but quickly rising to a plateau by early afternoon. In contrast, daily variations are much more modest following crystallization. Second, the quality of the match partially declines overnight, so that the pupil begins each day slightly worse than it left off the evening before.

Third, and perhaps most intriguingly, the greater the night-to-morning song deterioration during sensorimotor learning, the better the final match between the pupil's song and the tutor song. These observations suggest that during juvenile life, sleep triggers song deconsolidation, generating increased variability that enables the pupil to more fully 'search' vocal space in the quest to match the memorized tutor song.

3.23.3.4 Song Crystallization

3.23.3.4.1 A changing role for sensory feedback

Crystallized songs are not only more stereotyped than plastic songs but they also depend less acutely on auditory feedback (Konishi, 1965; Price, 1979). Deafening in juveniles leads to rapid song deterioration, whereas adult deafening in some species can exert little or no effect on the crystallized song (Konishi, 1965; Price, 1979). This implies that crystallization either transforms the song motor program into a feedback-independent 'read-only' system or that crystallized song maintenance is mediated by nonauditory (i.e., proprioceptive) forms of sensory feedback. Notably, when brief puffs of air are injected into the respiratory system of singing birds, respiratory and vocal muscles rapidly (~ 10 ms) compensate to maintain stable song output; these effects are seen even in deafened birds, indicative of proprioceptive feedback (Suthers et al., 2002). However, whether proprioceptive feedback is used for crystallized song maintenance remains untested.

The degree to which crystallized songs depend on auditory feedback varies across species. Pioneering studies by Mark Konishi indicated that crystallized songs of adult white-crowned sparrows were impervious to deafening (Konishi, 1965). In contrast, crystallized songs of adult zebra finches are maintained actively via auditory feedback: Adult deafening (Nordeen and Nordeen, 1992) or chronic exposure to distorted auditory feedback (Williams and McKibben, 1992; Leonardo and Konishi, 1999) triggers a slow process of song deterioration and plastic changes to the vocal pattern, known as decrystallization. Nonetheless, as with humans, deafening-induced vocal deterioration in zebra finches is slower in adults than in juveniles (Price, 1979; Cowie and Douglas-Cowie, 1992). Notably, adult Society finches, close relatives of the zebra finch, remain acutely dependent on auditory feedback, as their crystallized songs start to deteriorate several days to a week after deafening (Okanoya and Yamaguchi, 1997; Woolley and Rubel,

1997). In both zebra finches and Society finches, one idea is that the neural mechanisms enabling feedback-dependent learning in the juvenile also are employed to maintain stable song patterns in the adult.

3.23.3.4.2 Crystallization can impose innate constraints on song structure

A major insight is that crystallization can impose innate, species-typical constraints on song structure. Juvenile canaries tutored on synthetic songs provide an especially elegant demonstration of this effect (Gardner et al., 2005). In normal adult canaries, short stereotyped syllables are repeated to form phrases, which are linked together in the crystallized song. Synthetic 'phraseless' songs, in which syllables continuously vary in duration and amount of frequency modulation, can be used to tutor young canaries. Remarkably, juveniles first produce faithful imitations of such phraseless tutor songs but then impose phrasing with crystallization. Such innate constraints may explain why the songs of birds deafened early in life still exhibit crude but species-typical song features and why isolate songs are more similar within rather than across species. These innate mechanisms also could account for the conservation of song phenotype across geographically isolated breeding populations of the same species. If the brain of the naïve juvenile was truly a tabula rasa, then songs would randomly diverge across isolated populations, making such song conservation improbable.

3.23.3.4.3 Crystallization and critical periods for motor learning

Most evidence indicates that crystallization is not simply the result of successful learning but is the result of other factors – specifically testosterone. Male swamp and song sparrows castrated as juveniles develop plastic songs containing imitations of tutor songs, but they fail to undergo song crystallization unless implanted with testosterone (Marler et al., 1988). More generally, many seasonal songbirds crystallize their songs as vernal days lengthen and their testosterone levels rise but 'decrySTALLize' their songs as autumnal days shorten and their testosterone levels drop (Figure 2) (Nottebohm et al., 1987; Smith et al., 1997a). Thus, crystallization can be regulated by photoperiod-sensitive endocrine factors rather than the quality of the match to the tutor song.

Some evidence of an age-dependent component of crystallization comes from experiments in which botox injections were used to reversibly paralyze

syringeal muscles of juvenile zebra finches (Pytte and Suthers, 2000). When vocal paralysis spanned the period bracketing crystallization, the birds crystallized abnormal songs. In contrast, permanent disruptions in song quality were not observed when reversible paralysis was induced either earlier in sensorimotor learning or after crystallization.

Although this age-dependent effect may point to a critical period for sensorimotor learning, different aspects of this learning process may be regulated independently. As mentioned earlier, juvenile zebra finches can be prevented from copying previously memorized Society finch tutor songs by chronically exposing them to masking noise (Funabiki and Konishi, 2003). Such 'reversibly deafened' birds successfully imitated syllables from the memorized tutor songs when the noise was turned off between 100 to 200 days after hatching, one to several months after crystallization normally occurs in this species. However, the phrase structure of the Society finch tutor song was only imitated if the masking noise was turned off prior to day 80; otherwise, imitations consisted of Society finch notes organized into motifs typical of normal zebra finch songs. These results indicate that the closure of sensorimotor learning is not strictly age limited, at least when auditory feedback is blocked, and also hint that different aspects of sensorimotor learning, particularly note versus phrase imitation, are regulated independently.

3.23.3.4.4 Vocal plasticity following song crystallization

In seasonal birds such as swamp sparrows, syllables 'lost' during the initial round of crystallization may reappear in plastic songs in subsequent years, suggesting that they persist as auditory or motor memories (Marler and Peters, 1982a). Despite transient reexpression of 'lost' syllables, swamp sparrows nevertheless recrystallize the same subset of song types each summer. Those species that never alter their crystallized songs, which include zebra finches as well as North American sparrows, are referred to as 'closed-ended' or 'age-limited' learners (Figure 2) (Marler and Peters, 1987). In contrast, 'open-ended' or 'age-independent' learners, such as canaries, change their songs with each round of recrystallization (Figure 2) (Nottebohm and Nottebohm, 1978; Nottebohm, 1984). From a neurobiological perspective, this ongoing pattern of vocal 'exuberance' followed by attrition suggests that brain mechanisms engaged during sensorimotor learning in the juvenile can be reengaged in the adult.

3.23.4 Peripheral Mechanisms of Song Production

3.23.4.1 General Themes

Birds and mammals vocalize by inducing pressure waves in the expiratory air column. In general, this is achieved by passing air over vibrating membranes within a vocal organ. In humans, the vibratory elements are the vocal folds in the larynx. Although birds have a larynx, their vibratory element is in the syrinx, a specialized vocal organ unique to birds (Figure 5) (King, 1979).

The structure of the syrinx varies greatly across different avian taxa (King, 1979). General features of the syrinx are that it is located in the airway below the larynx, and it can be moved by sets of intrinsic and extrinsic muscles. The syrinx of oscine songbirds is a bipartite structure located at the confluence of the trachea and the two bronchi and contains a larger number of intrinsic muscles than in nonoscines (Figure 5). This sophisticated intrinsic musculature, the bipartite structure of the syrinx, and the highly specialized avian respiratory system enable virtuosic song displays.

A current view is that vocal output is determined by expiratory air pressure, syringeal muscle tension as air passes through the bronchial lumen, and filtering by the upper vocal tract (Suthers and Margoliash, 2002; Goller and Cooper, 2004; Suthers and Zollinger, 2004). Indeed, mathematical models indicate that small variations in the timing and magnitude of expiratory pressure and syringeal tension are sufficient to generate many of the acoustic features of birdsong (Mindlin, 2005).

3.23.4.2 The Syrinx: A Vibrating Vocal Organ

3.23.4.2.1 Anatomy and function of the syrinx

The oscine syrinx consists of a group of intrinsic muscles attached to specialized cartilaginous rings in caudal portions of the trachea and/or the primary bronchi (Figure 5) (King, 1979). In the upper bronchi, the medial parts of the rings are absent and instead consist of a sheer membrane, known as the medial tympaniform membrane (MTM). The cranial end of each bronchus is characterized by thickenings known as the medial and lateral labia. Over a century ago, Setherwall (1901) suggested that the syringeal labia were functionally analogous to the laryngeal

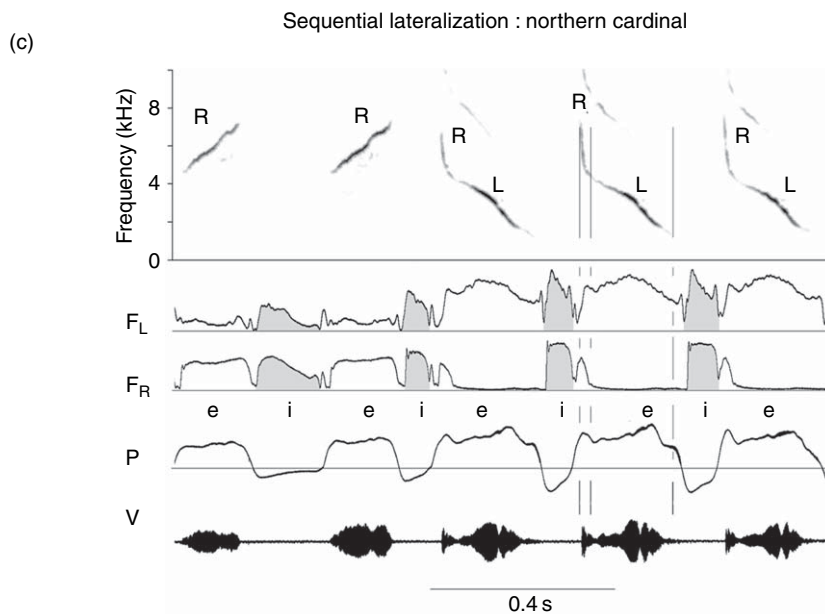
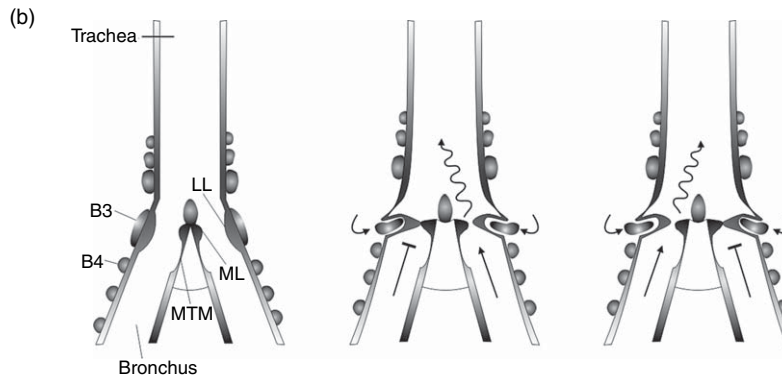
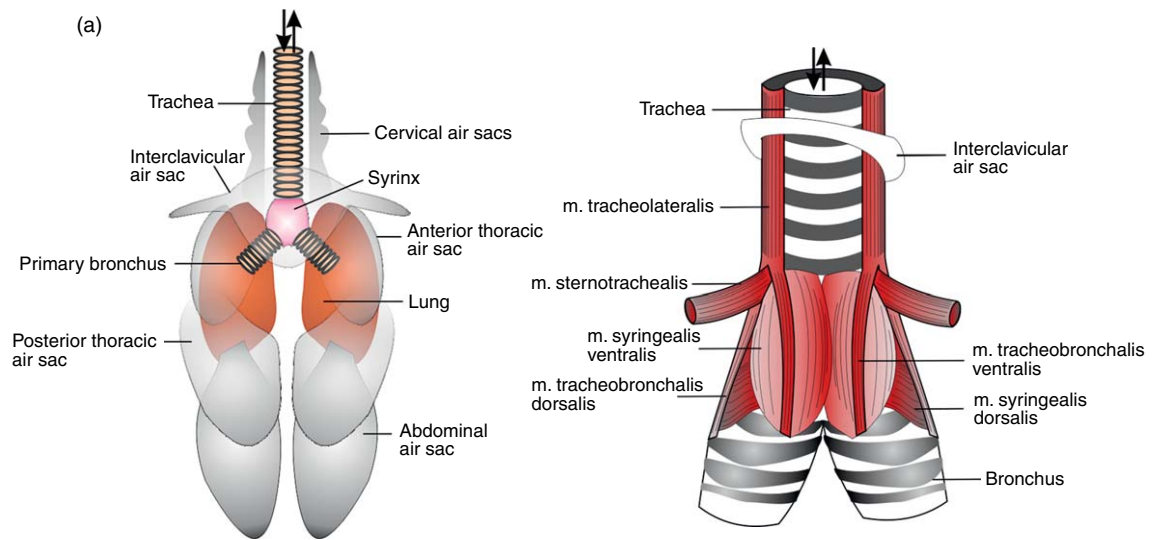
vocal folds. Miskimen (1951) later suggested that the MTM was the primary vibratory source of sound in the syrinx, an idea that dominated for several decades. The highly tonal quality of many birdsongs also led to an alternate, 'aerodynamic' hypothesis (Nottebohm, 1976; Gaunt et al., 1982; Gaunt, 1983; Casey and Gaunt, 1985), namely, that birdsong is not produced by a vibratory source but, instead, by air passing through a constricted bronchial lumen, which would act like a hole-tone whistle. Over the last several decades, Franz Goller, Roderick Suthers, and their colleagues used bronchial airflow measurements (Suthers, 1990; Goller and Suthers, 1996a,b) and endoscopic examination of the syrinx (Goller and Larsen, 1997; Larsen and Goller, 2002) in singing birds to show that song results from rapid vibrations in the syringeal labia, rather than by vibrations in the MTM or aerodynamic effects (Goller and Cooper, 2004; Suthers and Zollinger, 2004).

3.23.4.2.2 Ventral versus dorsal syringeal muscles

Studies by Suthers and his colleagues also lend considerable insight into the role of different syringeal muscles in birdsong. By using fine wires to record syringeal muscle activity while simultaneously measuring bronchial air flow and subbronchial air pressure in singing birds, Goller and Suthers determined that ventral syringeal muscle activity correlates with the song's fundamental frequency, while dorsal syringeal muscle activity controls air flow through the syrinx and thus sound output (Goller and Suthers, 1996a,b). This suggests that the different syringeal muscles can independently regulate the pitch and fine temporal features of song.

3.23.4.2.3 Independent control of the two sides of the syrinx

Songbirds exploit the bipartite structure of the syrinx to maximum effect. In several species, the two sides of the syrinx have been shown to move independently (Suthers, 1990; Goller and Suthers, 1995), greatly increasing fluency and vocal range (Zollinger and Suthers, 2004). Several species, including the brown thrasher, independently control the two sides of the syrinx to simultaneously sing two harmonically distinct sounds, a vocal effect termed the 'two-voice phenomenon' (Greenwalt, 1968; Suthers et al., 1994). The two sides of the syrinx also differ slightly in diameter, and thus in resonant frequency. The different resonant frequencies of the two sides allow



rapid alternation between notes of greatly contrasting pitch, an effect difficult to achieve with a unipartite vocal organ. The cardinal exploits these different resonances, skillfully and seamlessly switching from one side to the other to sing extremely broad frequency-modulated sweeps, or glissando notes (Figure 5(c)) (Hartley and Suthers, 1990; Suthers et al., 2004). Intriguingly, mockingbirds use a similar strategy when imitating the cardinal's glissando notes, suggesting constraints on peripheral song mechanisms (Zollinger and Suthers, 2004).

3.23.4.2.4 Nonlinear oscillatory properties intrinsic to the syrinx

Notably, some of birdsong's acoustical complexity results from nonlinear oscillatory properties intrinsic to the syrinx (Fee et al., 1998), rather than highly elaborate patterns of neuromuscular control. Experiments involving isolated syringes have shown that the syrinx displays nonlinear oscillatory dynamics in response to continuous variations in respiratory drive or syringeal activity (Fee et al., 1998). In terms of neural codes for song, modeling studies show that even simple and continuous changes in neuromuscular activity can trigger nonlinear modes of syringeal vibration, resulting in spectrally and temporally complex sounds (Mindlin et al., 2003; Mindlin, 2005).

3.23.4.3 The Avian Respiratory System and Temporal Control of Song

When songbirds sing, they exploit their specialized respiratory systems, which display impressive adaptations to the metabolic demands of flight (Scheid and Piiper, 1979). Unlike the tidal action of mammalian respiration, in which the lungs fill and empty with each respiratory cycle, avian respiration is unidirectional, with oxygenated air always flowing from the caudal to the rostral margin of the lung. This unidirectional flow is achieved by a series of highly inflatable air sacs that act like bellows to perfuse the relatively inflexible lungs (Figure 5(a)). The air sac system and very rapid inspiratory activity (i.e., mini-breaths) enable songbirds such as the canary to generate rapidly (5–30 Hz) trilled songs lasting tens of seconds (Suthers et al., 2004).

Measurements of air sac pressure can be used to estimate changes in the pressure head that drives air through the syrinx during singing (Suthers, 1990; Goller and Suthers, 1996a,b; Suthers and Zollinger, 2004). These measurements show that respiratory patterns determine the temporal structure of bird-song. In almost all species studied to date, sounds are produced during expiration, while silent intervals between notes and syllables correspond to inspiration (Figure 5(c)). Expiratory pulses may constitute

Figure 5 Anatomy of the songbird respiratory system and the syrinx, and their integrated activity during singing. (a) (left) The avian respiratory system is distinguished by a series of air sacs (gray) that function as bellows to move air through the relatively inflexible lungs. The songbird vocal organ, the syrinx, is a bipartite structure located at the junction between the primary bronchi and the trachea. (a) (right) Ventral view of the songbird syrinx and associated muscles. The syrinx is affected by six bilaterally paired muscles, each innervated by the tracheosyringeal branch of the ipsilateral hypoglossal nerve (XII_{ts}). These muscles control the movement and tension of the medial and lateral labia (ML and LL, respectively), thickenings at the cranial end of each bronchus within the syrinx (see b). (b) A cross section through the syrinx schematizing quiet respiration (left) and sequential lateralized airflow during phonation (middle and right). The trachea and bronchi consist of a series of cartilaginous rings; in the syrinx, the medial parts of the rings are absent and are replaced by the medial tympaniform membrane (MTM). During quiet respiration (left), the syringeal lumen is open on both sides. During singing (middle and right), contraction of the syringeal muscles (m. syringealis dorsalis and m. tracheobronchialis dorsalis) rotates the third bronchial cartilage (B3) into the syringeal lumen, forcing the LL and ML into the airstream and causing them to vibrate, resulting in sound (wavy lines). Phonation can be bilateral (not shown) or unilateral, when contraction of the syringeal muscles on one side of the syrinx is sufficient to completely block airflow. (a, b) Adapted from Suthers RA and Zollinger SA (2004) Producing song: The vocal apparatus. *Ann. N.Y. Acad. Sci.* 1016: 109–129. (c) The song of a northern cardinal illustrates sequential unilateral phonation during singing. The sonogram (top) shows a series of five syllables consisting of long frequency sweeps spanning as much 5 kHz. The lower panels are: airflow through the left (FL) and right (FR) sides of the syrinx (horizontal lines = zero air flow; e, expiration; i, inspiration, shaded grey); P, cranial air sac pressure (horizontal line = ambient pressure); V, oscillogram. The first two syllables, consisting of upward frequency sweeps, were generated largely by the right side of the syrinx. The following three syllables consist of long downward FM sweeps, with the initial high-frequency portion (between first and second vertical lines) produced through the right side of the syrinx and the final lower-frequency portion of the syllable produced by the left side. Figure courtesy of Rod Suthers. Images (a) and (b) courtesy of Todd Roberts. Image (c) courtesy of Rod Suthers.

fundamental motor units of song: Singing birds startled by brief stroboscopic flashes complete the ongoing syllable, only becoming silent at the end of the current expiratory cycle (Franz and Goller, 2002).

Ultimately, the song's temporal pattern is a product of precise control of expiration. Therefore, neural circuitry for song must control and coordinate both syringeal and respiratory motor activity. Indeed, separate neural pathways for respiratory and syringeal control exist in the songbird's brain (Wild, 1997a; Suthers and Margoliash, 2002), a point discussed in greater detail in following sections.

3.23.4.4 Syringeal Dynamic and Upper Vocal Tract Filtering

Songbirds and humans use their upper vocal tracts to filter vocal output. Indeed, simultaneous free field and syringeal recordings show that highly tonal sounds emitted at the beak correspond to harmonic series of tones emanating from the syrinx (Beckers et al., 2003). This discrepancy suggests that the trachea and beak selectively filter out certain harmonics emanating from the syrinx. In essence, the bird's upper vocal tract acts as a filter matched to certain wavelengths of sound produced by the syrinx. One way this filtering effect can be revealed is by placing birds in a helium–oxygen atmosphere (heliox); when notes are sung in heliox (Nowicki, 1987), they sound higher in pitch because the energy of the fundamental decreases while the energy of certain harmonics increases. This effect arises because the speed of sound increases in heliox while the fundamental frequency of syringeal vibration remains unchanged. As a consequence, the sound wavelength associated with syringeal vibration lengthens, no longer matching the filter. Instead, upper harmonics of the syringeal vibration better match the resonant properties of the upper vocal tract, imparting a higher pitch to the note.

The upper vocal tract of birds is a highly dynamic structure that can rapidly match the changing vibratory modes of the syrinx. The beak is part of this variable filter (Goller et al., 2004; Nelson et al., 2005; Fletcher et al., 2006); when the beak is opened wide, the effective length of the upper vocal tract shortens, raising the resonant frequency (Westneat et al., 1993). High-speed X-ray films of singing birds (Riede et al., 2006) show that the oropharyngeal cavity also is actively manipulated to dynamically alter the upper vocal tract resonance. These various observations

imply that the bird's brain must actively coordinate respiratory patterning, syringeal tension, and upper vocal tract dynamics to produce song.

3.23.5 Neural Circuits for Singing and Song Learning

3.23.5.1 General Themes

The foundation of songbird neurobiology rests on several major discoveries made over the past three decades. Arguably the most important of these was that the songbird's telencephalon exerts executive control of brainstem vocal-respiratory networks during singing, much as human language cortices command brainstem vocal-respiratory networks during speech (Doupe and Kuhl, 1999). This veritable epiphany stemmed from pioneering neuroanatomical and behavioral studies conducted by Fernando Nottebohm and his colleagues (Nottebohm et al., 1976, 1982; Nottebohm, 2005), who found that the songbird's brain contains a 'song system' – a constellation of interconnected nuclei necessary to singing (Figure 6).

Two telencephalic song nuclei, HVC and RA, are essential to singing and form a descending pathway that links the telencephalon to the brainstem vocal-respiratory network (Figure 6) (Nottebohm et al., 1976; Wild, 1997b). Intensive studies have yielded much information about the organization of this song motor pathway (SMP) and the nature of song motor 'codes' (Yu and Margoliash, 1996; Fee et al., 2004). Although the SMP has traditionally been viewed as a feedforward circuit, recent findings suggest that recurrent pathways from the brainstem to HVC contribute to song patterning (Ashmore et al., 2005).

A second key discovery was that the song system contains an anterior forebrain pathway (AFP) unnecessary to crystallized song but essential to song plasticity in both juvenile and adult birds (Figure 6) (Bottjer et al., 1984; Williams and Mehta, 1999; Brainard and Doupe, 2000; Olveczky et al., 2005). The AFP indirectly links HVC to RA and resembles mammalian cortical–basal ganglia (BG) pathways (Doupe et al., 2005). Experiments have revealed that the AFP helps generate acute song variability (Kao et al., 2005; Olveczky et al., 2005) and also acts over longer timescales to regulate the strength of synaptic connections between HVC and RA (Kittelberger and Mooney, 1999).

A final key discovery was that song nuclei display sensory as well as motor activity (Figure 6) (McCasland and Konishi, 1981). Auditory responses

highly selective for the bird's own song can be detected in the song system (Margoliash, 1983; Margoliash and Konish, 1985; Doupe and Konishi, 1991; Margoliash and Fortune, 1992; Mooney, 2000), and behavioral studies show that birds exhibit perceptual as well as vocal motor deficits when HVC or AFP nuclei are damaged (Brenowitz, 1991; Del Negro et al., 1998; Scharff et al., 1998a; Burt et al., 2000). Notably, the sensorimotor nature of HVC and the AFP resembles the expressive and receptive functions performed by language cortices in humans (Doupe and Kuhl, 1999). A major goal of current research is to understand whether auditory activity in the song system relays information about the memorized tutor song and/or auditory feedback.

3.23.5.2 Brainstem Vocal Respiratory Networks

3.23.5.2.1 General themes

Two key determinants of song structure – syringeal tension and respiratory patterning – are mediated by vocal respiratory networks in the brainstem and spinal cord (Figure 6). Substantial progress has been made in characterizing the anatomy of this vocal respiratory network. However, we still know relatively little about how these networks function during singing and the neural mechanisms that mediate upper vocal tract filtering (Wild, 2004).

3.23.5.2.2 The tracheosyringeal motor nucleus

The syringeal muscles are innervated by motor neurons in the tracheosyringeal part of the hypoglossal motor nucleus (XII_{ts}) (Nottebohm et al., 1976), a midline medullary nucleus situated caudal to the obex (Figure 6). XII_{ts} is myotopically organized: caudal XII_{ts} motor neurons innervate dorsal syringeal muscles, whereas rostral XII_{ts} motor neurons innervate ventral syringeal muscles (Vicario and Nottebohm, 1988). Syringeal motor neurons project ipsilaterally onto the muscles of the syrinx, providing one substrate for lateralized syringeal control. In certain songbird species, unilateral section of the XII_{ts} nerve exerts different effects on song depending on which side is cut (Nottebohm, 1971, 1977; Williams et al., 1992). This observation initially suggested that the central structures controlling song also may be lateralized, as cortical control of speech is lateralized in humans.

Syringeal motor neurons drive highly dynamic syringeal muscle activity during singing. When the XII_{ts}

nerve is cut, the spectral and fine temporal features of song are severely disrupted, while the global temporal features of song, which are determined by expiratory musculature, remain largely intact (Williams et al., 1989, 1992; Simpson and Vicario, 1990). The sparing of song temporal structure following XII_{ts} nerve section indicates that central pathways controlling syringeal and respiratory activity are independent. Indeed, these two control systems are partly segregated at the brainstem and at higher levels of the song system (Wild, 1993a,b; Reinke and Wild, 1998b; Suthers and Margoliash, 2002).

3.23.5.2.3 Brainstem and spinal cord respiratory networks

Expiratory and inspiratory motor neurons reside in the thoracolumbar and upper thoracic spinal cord, respectively (Wild, 2004). A cell column in the ventrolateral medulla, known as the ventral respiratory group (VRG), contains premotor neurons that innervate these expiratory and inspiratory motor neurons, thus controlling respiration (Figure 6) (Wild, 1994). The caudal VRG (nucleus retroambiguus [RAm]) controls expiration (Wild, 1993a,b), while the rostral VRG (nucleus paramambiguus [PAm]) controls inspiration (Reinke and Wild, 1998b). The VRG is bilaterally organized and reciprocally interconnected, with RAm neurons projecting throughout the ipsilateral and contralateral VRG (Figure 6). These bilateral projections, as well as the bilateral spinal projections of VRG axons, provide an anatomical substrate for bilateral coordination of respiration during song.

Vocalization requires precise coordination of respiratory and syringeal activity. The bilateral synaptic connections that VRG neurons make onto XII_{ts} motor neurons provide a substrate for this coordination and also are the likely source of the respiratory rhythm that can be recorded from XII_{ts} in nonvocalizing birds (Manogue and Paton, 1982; Williams and Nottebohm, 1985; Vicario, 1991a). Recordings made in brain slices show that XII_{ts} motor neurons receive inhibitory and excitatory inputs from the VRG (Sturdy et al., 2003); the inhibitory input may help establish the observed phase delays between onset of expiratory and syringeal muscle activity (Vicario, 1991a). Although XII_{ts} motor neurons are highly linear in their intrinsic firing properties (Sturdy et al., 2003), the extensive interconnectivity of the brainstem vocal-respiratory network may contribute to pattern generation beyond that provided by inputs from the telencephalic song premotor nucleus RA (Sturdy et al., 2003; Kubke et al., 2005).

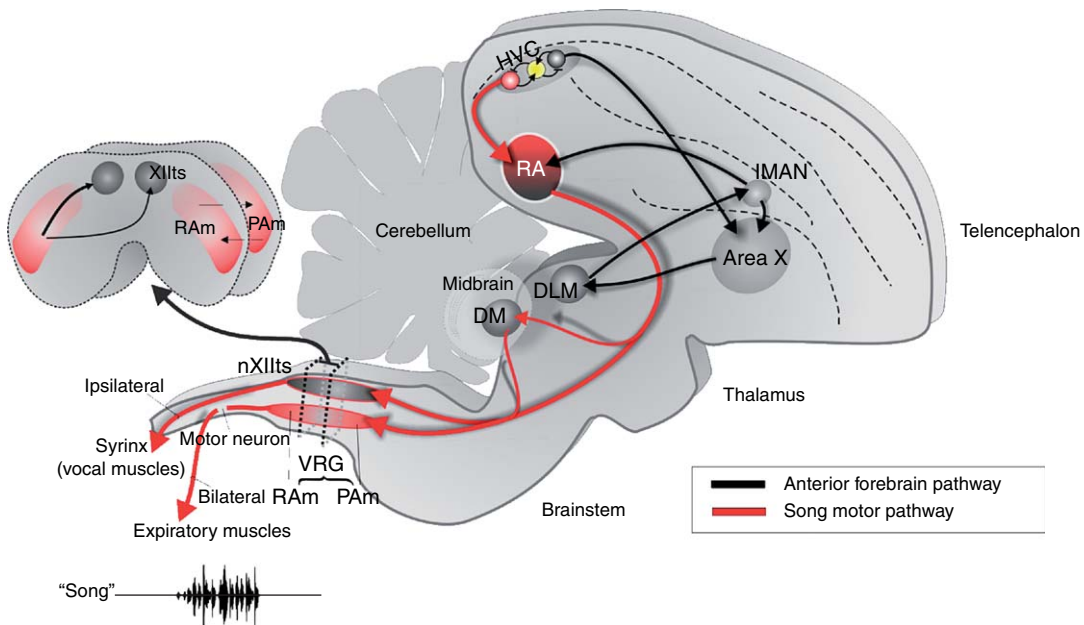
3.23.5.3 The Song System: Song Motor and Anterior Forebrain Pathways

3.23.5.3.1 The dawn of songbird neurobiology

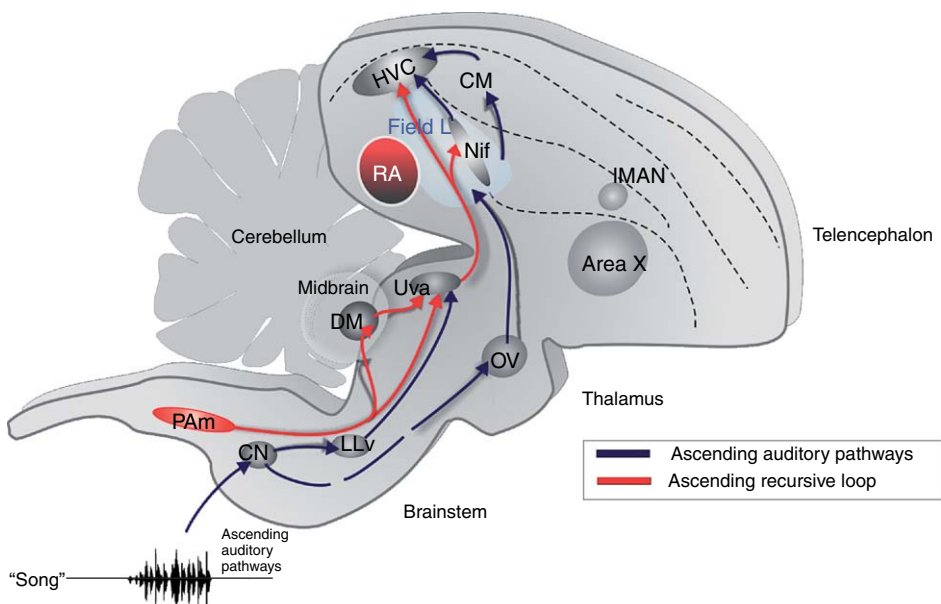
Songbird neurobiology took flight in the mid-1970s, when Fernando Nottebohm, Tegner Stokes, and

Christiana Leonard discovered that specialized nuclei in the songbird's telencephalon are essential to singing. In a landmark study (Nottebohm et al., 1976), Nottebohm and his coworkers showed that bilateral lesions to one of these nuclei, now referred to simply as 'HVC,' rendered an adult male canary

Descending song motor & anterior forebrain pathways



Ascending auditory & song motor feedback pathways



mute for song, even though it readily assumed a singing posture when presented with a female canary and produced unlearned calls normally. Anterograde tracing revealed two efferents of HVC: the robust nucleus of the arcopallium (RA), in the caudal telencephalon, and area X, in the avian basal ganglia. As its rather mysterious-sounding name might imply, lesions to area X exerted no obvious effect on crystallized song. However, RA lesions profoundly disrupted song, and tracing studies revealed that RA axons terminated in XIIts, suggesting that RA was a song premotor nucleus. This study showed that birdsong, unlike most other animal vocalizations save perhaps human speech, involves direct telencephalic control of vocal motor neurons.

3.23.5.3.2 Current overview of song system anatomy

In the past 30 years, a fully fledged song system has taken wing (Nottebohm, 2005). This system can be divided into two major components: a song motor pathway (SMP) and an anterior forebrain pathway (AFP) (Nottebohm et al., 1976), which both emanate from HVC and converge in RA (Figure 6). The SMP and the AFP arise from distinct pools of projection neurons (PNs) located in HVC (Katz and Gurney, 1981; Kirn et al., 1991; Fortune and Margoliash, 1995; Mooney, 2000). One HVC PN type (HVC_{RA}) provides excitatory input onto RA PNs (Mooney, 1992),

which innervate syringeal motor neurons and respiratory premotor neurons (Nottebohm et al., 1976; Wild, 1993b). The other PN type (HVC_X) innervates area X, which is part of a serially connected pathway that indirectly links HVC to RA and includes the thalamic nucleus DLM and the anterior telencephalic nucleus LMAN (Nottebohm et al., 1982; Okuhata and Saito, 1987; Foster and Bottjer, 1998). The axons of LMAN PNs bifurcate, with one branch innervating area X (Nixdorf-Bergweiler et al., 1995) and the other forming excitatory synapses on the same RA PNs that receive input from HVC (Mooney, 1992). Targeted photoablation of HVC_{RA} but not HVC_X neurons grossly disrupts song (Scharff et al., 2000), mirroring the differential effects of RA versus area X lesions (Nottebohm et al., 1976) and reinforcing the idea that HVC_{RA} neurons drive song premotor activity in RA. Ultimately, the SMP and AFP arise from different pools of HVC PNs and converge on song premotor neurons in RA that constitute the sole forebrain output of the song system.

The nucleus RA displays anatomical features likely to facilitate selective control of syringeal and respiratory activity. First, neurons located in ventral and medial RA project onto rostral and caudal XIIts (Vicario, 1991b), respectively. Because these different parts of XIIts ultimately innervate different syringeal muscle groups (Vicario and Nottebohm, 1988), activity in different parts of RA could recruit different

Figure 6 Specialized neural circuits in the songbird's brain, collectively referred to as the 'song system,' enable singing and song learning. (a) The song motor pathway (SMP; red) and the anterior forebrain pathway (AFP; black) are schematically illustrated in a parasagittal section through the songbird brain. The SMP arises from neurons in HVC (HVC_{RA} neurons) that project directly to the robust nucleus of the arcopallium (RA). RA in turn provides song motor output from the telencephalon through its projections onto syringeal motor neurons in the tracheosyringeal portion of the hypoglossal motor nucleus (XIIts) and onto respiratory premotor neurons in a column of cells in the ventrolateral medulla known as the ventral respiratory group (VRG). The VRG comprises the nucleus retroambigualis (RAm), which controls expiration, and the nucleus parambigualis (PAm), which controls inspiration. RA also projects onto the dorsomedial intercollicular nucleus (DM) in the midbrain, which also innervates XIIts and the VRG; DM plays a role in call generation in birds. The anterior forebrain pathway (black arrows) arises from a distinct population of HVC neurons (HVC_X neurons) that innervate area X (part of the songbird basal ganglia). Large inhibitory neurons in area X project axons onto the medial nucleus of the dorsolateral thalamus (DLM), which in turn provides excitatory input to the lateral portion of the magnocellular nucleus of the anterior nidopallium (LMAN). Axons from LMAN innervate area X and also innervate the same song premotor neurons in RA that receive input from HVC_{RA} neurons. Thus, the SMP and AFP arise from distinct pools of HVC projections neurons and innervate the same RA song premotor neurons. (b) Pathways that are believed to convey auditory and recurrent song motor information to HVC. Auditory information (blue arrows) originates in the inner ear and passes via the eighth cranial nerve to the cochlear nucleus (CN) in the medulla, where it is relayed indirectly to HVC through two pathways. The first pathway includes the ventral portion of the lateral lemniscus (LLv) and the thalamic nucleus uvaformis (Uva). The second pathway includes an indirect pathway (broken line) through the auditory hindbrain and midbrain (not shown) to the thalamic nucleus ovoidalis (Ov); axons from Ov terminate in the massively interconnected telencephalic area Field L, which is analogous to mammalian primary auditory cortex. From Field L, activity is relayed through an interconnected network comprising the caudal medial nidopallium (NCM) and the caudal mesopallium (CM), which in turn projects directly to HVC and indirectly to HVC through the nucleus interfascialis (Nif). Song motor-related feedback and possibly respiratory-related activity from the brainstem are thought to reach HVC through a recurrent circuit (red lines) that includes PAm, DM, Uva, and Nif. Images courtesy of Todd Roberts.

syringeal muscles. Second, neurons in dorsal RA terminate on regions of the lateral medulla containing respiratory premotor neurons (Wild, 1993b). This segregated organization may enable dorsal and ventral RA neurons to independently modulate respiratory and syringeal activity. Third, RA axons terminate on several structures in the thalamus and midbrain, including the dorsomedial intercollicular nucleus, an area implicated in the generation of innate calls (Wild, 1993b; Wild et al., 1997). Although the function of this latter connection is unknown, one possibility is that RA interacts with DM to suppress call generation during singing. Finally, RA neurons do not directly innervate the glossopharyngeal, facial, and trigeminal motor nuclei that control the upper vocal tract (Wild, 1993b), which suggests that RA influences the upper vocal tract indirectly via the VRG.

The gross structure of HVC and RA correlates with song function. First, these nuclei are absent in birds that do not learn their songs, including flycatchers (Kroodsma and Konishi, 1991), close cousins to the oscines. Second, in those species where only the male sings, HVC and RA are greatly reduced in the female (Nottebohm and Arnold, 1976); such dimorphisms are lacking in duetting species where both sexes sing (Brenowitz et al., 1985). Finally, in seasonal breeders, HVC and RA expand in volume in the spring, when the bird sings a crystallized song, and shrink in the fall, when the bird sings less frequent and more acoustically variable songs (Nottebohm, 1981; Smith et al., 1997b; Brenowitz, 2004).

Despite these gross variations in song system structure, anatomical correlates of song lateralization have remained elusive (DeVoogd and Nottebohm, 1981; Nottebohm et al., 1981). Therefore, peripheral asymmetries in the vocal apparatus and more subtle central specializations underlie the lateralized effects of XIIIts nerve section. More generally, the descending projections of the forebrain song nuclei are entirely ipsilateral, and in some species the projections from RA to the brainstem also are ipsilateral (Wild et al., 2000). This arrangement presumably enables distinct motor programs to be sent to the two sides of the syrinx.

3.23.5.3.3 *Singing-related neural activity in the SMP*

Chronic electrophysiological recordings made in singing birds have illuminated the neural dynamics underlying song. A pioneering effort by McCasland and Konishi showed that bursts of activity in HVC

and RA occurred before and during the utterance of individual syllables; premotor activity also could be detected in the nucleus interface (NIf), a telencephalic structure presynaptic to HVC (McCasland and Konishi, 1981). A latency analysis supported the notion of a song motor hierarchy, with a feedforward flow of song motor activity propagating from NIf through HVC, RA, and the brainstem.

Although far ahead of its time, McCasland's study relied on multiunit recording methods, making it difficult to determine how song is encoded at different levels of the SMP. A series of elegant single-unit recording studies overcame this limitation, providing us with a detailed picture of how song motor codes change between HVC and RA (Figure 7). A particularly elegant study by Richard Hahnloser, Alex Kozhevnikov, and Michale Fee used a miniature motorized microdrive in the zebra finch to show that single HVC_{RA} neurons fire one brief (~10 ms) burst of action potentials at precisely the same time in each motif, with different HVC_{RA} neurons firing at different times during the motif (Figures 7(a) and 7(c)) (Hahnloser et al., 2002). Although only a relatively small number of neurons were sampled from any one bird, this finding implies that sparse activity propagates in a rapid (~100 Hz) clocklike fashion rapidly through the entire HVC_{RA} population, spanning the whole motif. Other groundbreaking studies by Albert Yu and Dan Margoliash, and by Anthony Leonardo and Michale Fee, found that single RA PNs burst at many (~10) precise times during a motif, in contrast to the temporally sparse firing patterns of individual HVC_{RA} neurons (Figures 7(b) and 7(d)) (Yu and Margoliash, 1996; Leonardo and Fee, 2005). Intriguingly, recordings made in sleeping birds show that HVC_{RA} and RA neurons generate spontaneous activity patterns similar to those they exhibit during singing (Dave and Margoliash, 2000), suggesting that the SMP 'replays' song motor programs during sleep.

3.23.5.3.4 *Models of song patterning networks*

The acoustic features of song span many timescales: milliseconds for internote intervals, tens to hundreds of milliseconds for notes and syllables, and one to tens of seconds for an entire song. Several circuit models have been put forth to account for patterning of notes, syllables, and songs. Aspects of all of these models find at least partial support in experimental observations.

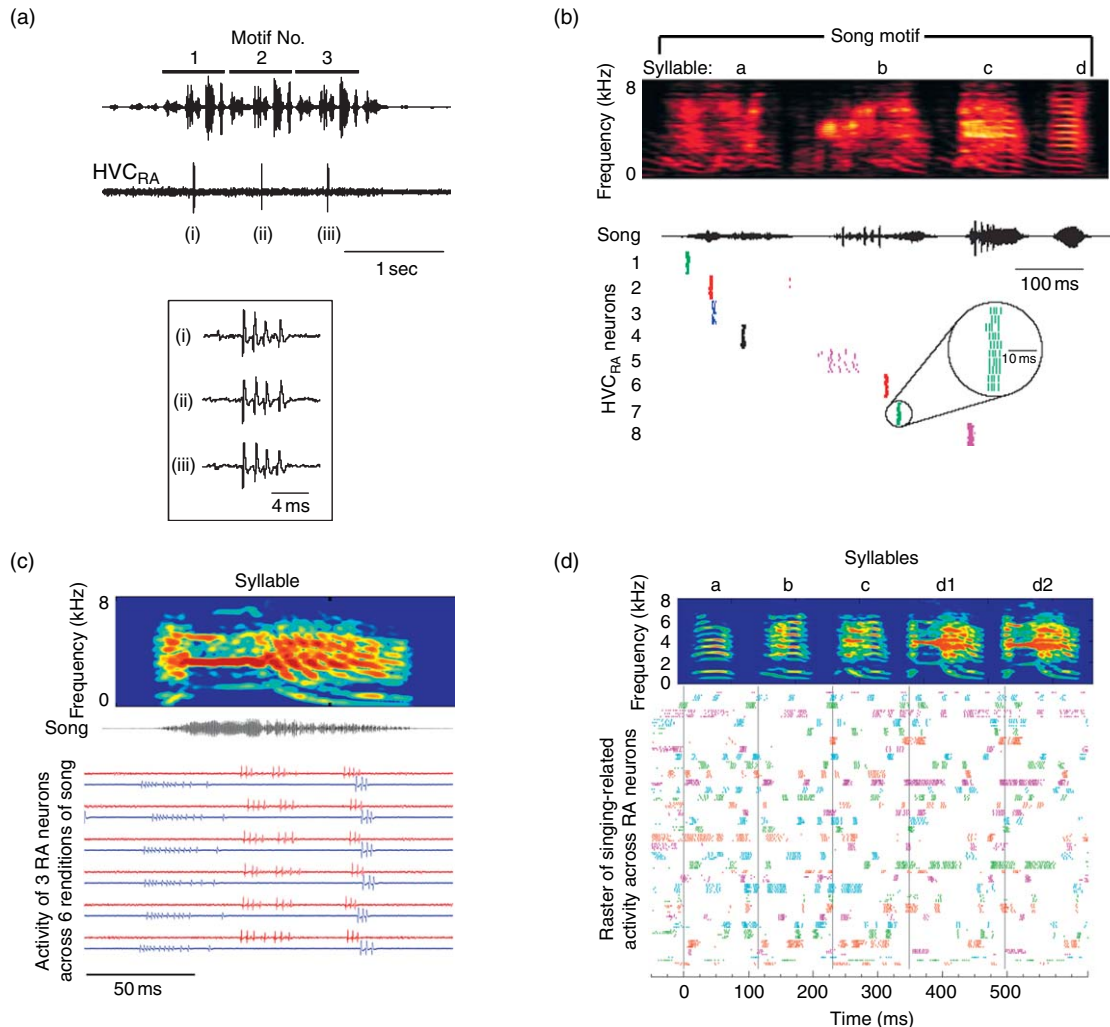


Figure 7 Chronic recordings of single-unit activity in singing zebra finch suggest that neuronal codes for song are transformed from an ultrasparse temporal representation in HVC to a more continuous representation in RA. (a) Individual HVC_{RA} neurons fire a single brief burst of action potentials at one precise time in each motif (top, song oscillogram; bottom, simultaneously recorded neural activity; inset, expanded time base showing structure of the burst). (b) Different HVC_{RA} neurons are active at different points in the motif, suggesting that the entire ensemble of HVC_{RA} neurons provides a fine timescale representation of song (top, sonogram; middle, oscillogram; bottom, raster display of action potential activity for eight different color-coded HVC_{RA} neurons over ten renditions of the motif). (a, b) Reprinted by permission from Macmillan Publishers Ltd: Hahnloser RH, Kozhevnikov AA, and Fee MS (2002) An ultra-sparse code underlies the generation of neural sequences in a songbird. *Nature* 419: 65–70, copyright 2002. (c) Singing-related activity in RA neurons is temporally precise over multiple renditions of the same syllable but is temporally more continuous than in HVC_{RA} neurons (top, sonogram of the syllable; bottom, blue and red records show data aligned to the syllable acquired from different electrodes in RA). (d) Motif-aligned activity of 34 RA neurons recorded from the same bird (top, sonogram of the motif) reveals that each RA neuron exhibited multiple (~10) bursts of activity, the timing of which was similar across different renditions of the motif but generally different from the timing of burst activity in other RA neurons. Different neurons are represented by different colors, with different motif renditions represented by different rows of the raster display. (c, d) Reprinted from Leonardo A and Fee MS (2005) Ensemble coding of vocal control in birdsong. *J. Neurosci.* 25: 652–661.

In the music-box model, the entire HVC_{RA} population can be likened to the programming cylinder in a music box, with the subset of HVC_{RA} neurons active at any instant constituting an individual pin on this

cylinder (Figure 8) (Fee et al., 2004). A pattern of divergent and convergent feedforward connections transforms temporally sparse activity from these HVC_{RA} ‘pins’ into more continuous activity in RA,

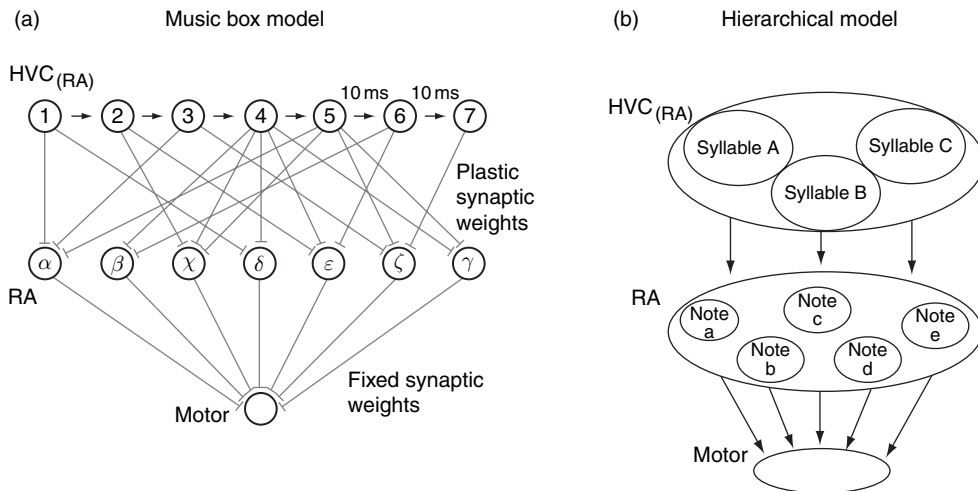


Figure 8 Schematic diagrams illustrating the music box (A) and hierarchical (B) models for song generation. (a) In the music-box model, each HVC_{RA} neuron is active at only one time in the song motif and activity propagates in 10-ms steps through the entire HVC_{RA} ensemble to span the entire motif. A pattern of divergent and convergent HVC / RA synapses translates this temporally sparse activity into a more continuous activity pattern in individual RA neurons, the output from which is transformed by the brainstem motor system into song. A central component of this model is that HVC encodes timing information about song but does not explicitly represent any acoustical features of the song, such as syllables or notes. Reprinted from Leonardo A and Fee MS (2005) Ensemble coding of vocal control in birdsong. *J. Neurosci.* 25: 652–661. (b) In the hierarchical model, HVC encodes large-scale song features, such as syllables. Neurons within RA code for finer-grain song features, such as individual notes.

which then modulates the vocal respiratory system to generate song. In its simplest form, the HVC_{RA} ensemble constitutes a relatively fast (~100 Hz) metronome that, via its synaptic connections with RA, dictates the timing of syllables, notes, and even intersyllable gaps. Interestingly, some HVC_{RA} and RA neurons do burst during silent periods between notes and syllables, suggesting that these song premotor nuclei could encode the timing of silent gaps as well as audible components in the song. Because song output in the music-box model is determined by the specific pattern of synapses HVC_{RA} neurons make in RA, error signals presumably act within RA to alter these connections during sensorimotor learning. In fact, modeling studies show that temporally sparse activity in HVC optimizes learning rates, because error signals that ‘correct’ the connections of an HVC_{RA} neuron only introduce changes at a single time in the motif (Fiete et al., 2004).

Another feedforward model involves a hierarchical patterning network, with syllables or motifs encoded in ‘higher’ areas, such as HVC, and lower-level features, such as notes, encoded in RA and the brainstem (Figure 8) (Yu and Margoliash, 1996). One early observation supportive of a hierarchy was that HVC microstimulation in the singing zebra finch could reset the entire motif, while RA stimulation only

interrupted the ongoing note (Vu et al., 1994). Although consistent with a hierarchical model, electrical stimulation in HVC also activates areas presynaptic to HVC, such as NIf and the thalamic nucleus Uva, and thus any higher-level patterning mechanisms may not be localized to HVC. A recent comprehensive temporal analysis of zebra finch songs shows that, as the song tempo varies, syllables scale much less elastically than do intersyllable gaps (Glaze and Troyer, 2006), implying these features are regulated independently. These behavioral observations are consistent with a hierarchical model and contrast with the music-box model, where syllables and gaps should scale proportionally with variations to the overall song tempo.

In contrast with these two feedforward models, a third idea is that recurrent pathways from the brainstem modulate forebrain song patterning networks, establishing a distributed and possibly circular hierarchy. Indeed, a recent study showed that motif resetting could be triggered by microstimulation in HVC, RA, and even the RVG (Ashmore et al., 2005), a set of observations difficult to reconcile with the strictly feedforward architectures of the music box or hierarchical models. Instead, these results indicate that recurrent pathways from the brainstem to the forebrain likely contribute to song temporal

structure. An anatomical substrate for this recurrent pathway is provided by a subset of RVG axons that project bilaterally to the thalamic nucleus Uva, which in turn innervates HVC and Nif (Reinke and Wild, 1998a; Striedter and Vu, 1998). Because the RVG contains respiratory premotor neurons and receives descending input from RA, it may provide forebrain song nuclei with respiratory information and recurrent song-related motor activity important to setting the song temporal pattern, including the timing of syllable transitions. In addition, because songbirds lack a cerebral commissure, the bilateral projections from RVG to Uva are the most likely substrate for the precise bilateral coordination of song premotor activity seen in HVC. Notably, this recurrent model does not rule out a role for HVC in generating a fine timescale code for song patterning, but such a code would be under the influence of the recurrent loop.

Regardless of which model is most accurate, HVC displays network features that could serve an important role in song patterning. In an isolated HVC preparation, trains of electrical pulses evoke sustained trains of quasi-rhythmic synaptic potentials in HVC neurons (Solis and Perkel, 2005). Additionally, HVC PN and inhibitory interneurons are reciprocally connected (Mooney and Prather, 2005), a synaptic motif known to sustain oscillatory activity in other pattern-generating networks (Selverston and Moulins, 1985). Whether endogenous pattern generation is unique to HVC is unclear, however, because complex local synaptic networks exist within RA (Spiro et al., 1999) and in the respiratory-vocal brainstem (Sturdy et al., 2003; Kubke et al., 2005) and may be capable of generating rhythmical activity independent of input from HVC.

3.23.5.4 The Role of the Anterior Forebrain Pathway in Song Plasticity

3.23.5.4.1 The AFP is a basal ganglia pathway necessary to song plasticity

The AFP forms intimate links with the SMP: area X is innervated by HVC, and the AFP output, nucleus LMAN, innervates RA (Nottebohm et al., 1976, 1982). Despite direct connections between the AFP and song premotor structures, initial behavioral studies showed that adult crystallized songs were unaffected by lesions to either area X or LMAN (Nottebohm et al., 1976; Bottjer et al., 1984; Sohrabji et al., 1990). A breakthrough came in 1984, when Sarah Bottjer and her coworkers discovered that bilateral LMAN lesions in juvenile zebra finches

caused their plastic songs to degrade rapidly and become much less variable, assuming a highly repetitive and simplified form (Bottjer et al., 1984). A subsequent analysis of area X lesions made in juvenile birds showed that songs in these birds remained highly variable into adulthood, never achieving the stereotypy typical of crystallized song (Sohrabji et al., 1990; Scharff and Nottebohm, 1991).

These age-dependent effects of AFP lesions lent support to the idea that the AFP plays a developmentally restricted role in song learning. However, more recent findings show that the AFP also is necessary to adult forms of song plasticity. Rather remarkably, LMAN lesions block the song deterioration (i.e., decrystallization) normally triggered in adult zebra finches by deafening (Figure 9) (Brainard and Doupe, 2000) or by exposure to chronically distorted auditory feedback (Williams and Mehta, 1999). An important implication is that decrystallization is an active process requiring the AFP and not simply a degenerative process. The AFP also plays an ongoing role in adult song recrystallization; adult white-crowned sparrows subjected to LMAN lesions during the winter, prior to the annual reexpression of plastic song, failed to successfully recrystallize their songs (Benton et al., 1998). Finally, song learning in adult isolates also has been shown to be blocked by LMAN lesions (Morrison and Nottebohm, 1993), further underscoring that the AFP's role in song plasticity is not age limited.

The specific means by which the AFP contributes to song plasticity is of great interest. One way the AFP could enable song plasticity is by generating acute song variations that serve as 'stepping stones' for larger and more gradual changes to song. Over longer timescales, the AFP also might enable song plasticity by exerting trophic effects on synapses in the SMP. In either case, the AFP could play either a permissive or instructive role to enable song learning.

3.23.5.4.2 LMAN plays an acute role in generating song variability

Understanding the synaptic connections that LMAN makes with RA can inform how the AFP could influence song plasticity. Morphological and electrophysiological studies reveal that RA song premotor neurons receive convergent excitation from both HVC and LMAN axon terminals (Canady et al., 1988; Mooney and Konishi, 1991; Mooney, 1992). Both inputs excite ionotropic glutamate receptors on RA PN dendrites, but near the resting membrane potential, those from LMAN predominantly activate

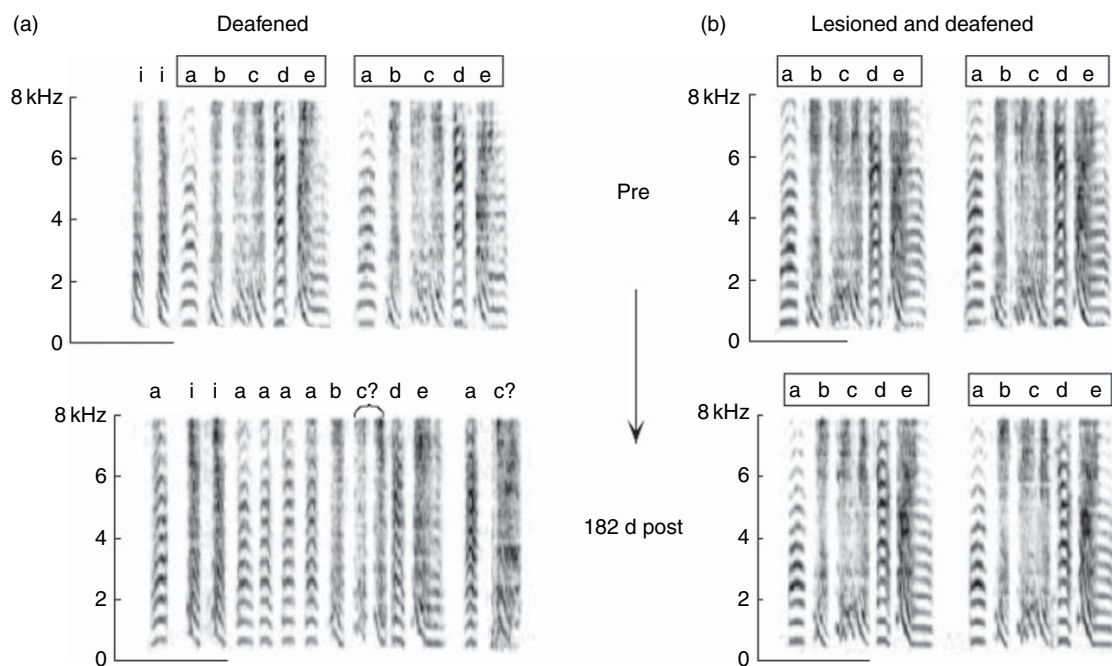


Figure 9 An intact AFP is necessary for deafening-induced song decrystallization in adult zebra finches. (a) Sonograms of an adult zebra finch before and 182 days after deafening reveal changes in the structure of the bird's song, including stuttered syllables ('a'), altered syllable morphology ('?'), and changes to the syllable sequences ('a-c-?'). (b) Bilateral lesions in LMAN made prior to adult deafening prevent changes to song structure. Reprinted by permission from Macmillan Publishers Ltd: Brainard M and Doupe A (2000) Interruption of a forebrain-basal ganglia circuit prevents plasticity of learned vocalizations. *Nature* 404: 762–766, copyright 2000.

postsynaptic *N*-methyl-D-aspartate (NMDA) receptors, while those from HVC predominantly activate alpha-amino-3-hydroxy-5-methyl-4-isoxazole propionic acid (AMPA) receptors (Kubota and Saito, 1991; Mooney and Konishi, 1991; Mooney, 1992). Differential activation of NMDA and AMPA receptors in other pattern-generating networks leads to different output patterns (Dale and Roberts, 1984; Dye et al., 1989), suggesting that differential activation of LMAN and HVC inputs onto RA neurons could lead to song variability.

Indeed, several observations show that LMAN drives acute song variability. First, pharmacologically inactivating LMAN in juvenile zebra finches rapidly and reversibly reduces note and sequence variability in their plastic songs (Olviczky et al., 2005). Blocking NMDA receptors in RA exerts similar effects, underscoring that LMAN drives song variability via its synaptic connections with song premotor neurons (Olviczky et al., 2005). Second, microstimulation in LMAN can drive slight variations in song of adult zebra finches (Kao et al., 2005). Third, LMAN neurons are active during both directed and undirected singing in adult zebra finches, but during the more variable undirected singing, they burst at higher

frequencies and in more variable patterns (Kao and Brainard, 2006). Finally, the acoustic variability of undirected songs is abolished by LMAN lesions (Kao and Brainard, 2006). Ultimately, these various findings indicate that in both the juvenile and the adult, LMAN operates over a short timescale (tens to hundreds of milliseconds) to drive song variability.

The details of AFP connectivity provide a useful context in which to interpret the effects of AFP lesions on song variability. The AFP bears strong similarities to mammalian cortical-basal ganglia pathways (Doupe et al., 2005), with HVC and LMAN providing the 'cortical' input and output and area X and the medial part of the dorsolateral thalamus (DLM) the interposed basal ganglia and thalamic 'relays.' The basal ganglia homologue area X comprises many different cell types, including a smaller GABAergic cell type (SN) that resembles mammalian striatal medium spiny neurons and a larger pallidal-like GABAergic cell type (AF) that makes massive inhibitory synapses onto DLM neurons (Luo and Perkel, 1999; Ding and Perkel, 2002; Farries and Perkel, 2002). These thalamic neurons make excitatory synapses onto LMAN neurons

(Livingston and Mooney, 1997; Boettiger and Doupe, 1998), which in turn form excitatory synapses on RA neurons (Mooney and Konishi, 1991). Because AF neurons fire spontaneously at high rates (Farries and Perkel, 2002), a reasonable assumption is that, at 'resting' levels, DLM neurons are tonically inhibited and LMAN activity remains low. Conversely, factors that suppress AF neuron firing would release DLM neurons from inhibition, ultimately rendering LMAN neurons more active (Person and Perkel, 2005). Indeed, this connectivity provides a useful context in which to understand the contrasting behavioral effects of LMAN and area X lesions: LMAN lesions abolish activity necessary to driving acute song variability, whereas lesions to area X remove tonic inhibition on DLM, increasing LMAN activity and generating higher levels of song variability. If this model is correct, then a key to understanding endogenous regulation of song variability will rest on determining how afferents to area X, which include HVC and midbrain dopamine neurons, influence AF neuron activity.

3.23.5.4.3 Trophic regulation of HVC–RA connectivity by LMAN

In addition to driving bout-to-bout variability, LMAN also could affect song plasticity by exerting trophic effects on RA. As seen more widely in the developing vertebrate central nervous system (CNS), synaptic density in RA describes an inverted 'U' over development, with numbers of HVC axon terminals and RA dendritic spines reaching a peak during the height of sensorimotor learning (Herrmann and Arnold, 1991; Kittelberger and Mooney, 1999). Both of these parameters decline markedly by crystallization, indicative of synapse elimination, while the remaining HVC > RA synapses increase in strength, suggestive of synapse consolidation (Herrmann and Arnold, 1991; Kittelberger and Mooney, 1999).

One idea is that, in the juvenile, LMAN actively maintains RA microcircuitry in a state permissive for song plasticity. Consistent with this idea, LMAN lesions trigger a rapid consolidation of HVC > RA synapses like the consolidation that occurs gradually over normal development (Kittelberger and Mooney, 1999). These experiments show that HVC > RA synapses in juvenile songbirds are highly plastic, and that LMAN plays a role in regulating this synaptic plasticity. These studies also suggest that a normal developmental decline in the number or efficacy of LMAN synapses in RA could consolidate HVC > RA synapses, leading to persistent changes in song. Candidates for mediating this trophic effect include

the brain-derived neuronotrophic factor (BDNF), which is expressed in both LMAN and HVC_{RA} neurons (Johnson et al., 1997; Akutagawa and Konishi, 1998; Li et al., 2000), and which at earlier stages of development has been shown to rescue RA neurons from cell death triggered by LMAN lesions (Johnson et al., 1997). Consistent with the idea that BDNF acts as a permissive signal for song plasticity, BDNF injections into the RA of the adult zebra finch simultaneously elevate song variability and augment the density of HVC terminals in RA (Kittelberger and Mooney, 2005).

3.23.5.4.4 The AFP and critical periods for song plasticity

The means by which LMAN enables song plasticity also suggest mechanisms of song crystallization. One possibility is that crystallization arises as a result of decreased variability in LMAN firing patterns during singing. In support of this idea, the acoustic variability of undirected song and the variability of LMAN activity decline in parallel as adult zebra finches grow older (Kao and Brainard, 2006). Crystallization also could arise because the 'gain' of LMAN synaptic currents decreases in adults. In fact, LMAN > RA synaptic currents shorten in duration between juvenile and adult life (Stark and Perkel, 1999; White et al., 1999; Livingston et al., 2000), likely because of an elevation in the NR2A:NR2B subunit ratio of postsynaptic NMDA receptors (Scott et al., 2004). A shortening of LMAN > RA synaptic timecourse also can be precipitated rapidly in juvenile zebra finches by testosterone implants (White et al., 1999), a treatment that also impairs sensorimotor learning (Korsia and Bottjer, 1991). Moreover, the NR2A:NR2B subunit ratio in the RA of the adult canary waxes and wanes in parallel with changes in day length, testosterone titers, and song stereotypy (Singh et al., 2003). Thus, changes to the firing patterns of LMAN neurons and the efficacy of their synapses in RA could underlie the decline in song variability that occurs with song crystallization.

3.23.5.5 Auditory Roles of the Song System: Templates, Feedback, and Error Signals

3.23.5.5.1 General themes

The neural components underlying a template model of song learning include a motor pathway for song production, an auditory memory of the tutor song (i.e., a template), and a mechanism for comparing singing-related auditory feedback to the template (Konishi, 1965, 2004). When this 'comparator' detects

mismatches between the feedback signal and the template, it generates an error signal that modifies motor activity in the song production pathway, with the eventual result that the bird's song comes to resemble the tutor song. In addition to a song motor role, several lines of evidence suggest that the song system also may serve one or more auditory roles, including song recognition, template storage, conveying auditory feedback, or processing the resulting error signal. One piece of evidence is that auditory responses can be detected throughout the song system (Katz and Gurney, 1981; Margoliash, 1983; Williams and Nottebohm, 1985; Williams, 1989; Doupe and Konishi, 1991). Second, some song system neurons respond selectively to the bird's own song (BOS) and to the tutor song, indicating that they encode aspects of the bird's auditory experience (Margoliash, 1986; Solis and Doupe, 1999). Third, lesions to HVC or the AFP impair song recognition, suggesting auditory activity in the song system serves a perceptual role (Brenowitz, 1991; Scharff et al., 1998b; Burt et al., 2000). Finally, the presence of auditory activity in the AFP, a pathway necessary to song learning, raises the possibility that it conveys either feedback

or the resulting error signal to the SMP (Doupe and Konishi, 1991; Brainard and Doupe, 2000).

3.23.5.5.2 Auditory responses in the song system

Intriguingly, the earliest chronic recordings of singing-related neural activity conducted in HVC also detected robust responses to auditory presentation (i.e., playback) of the BOS (McCasland and Konishi, 1981). Subsequent playback studies, mostly in anesthetized zebra finches, detected auditory responses throughout the AFP and the SMP, even in the hypoglossal nerve (Margoliash, 1983, 1986; Williams and Nottebohm, 1985; Doupe and Konishi, 1991). The source of this widespread auditory activity is HVC, which transmits auditory activity to the SMP and the AFP via its two populations of projection neurons (Doupe and Konishi, 1991; Vicario and Yohay, 1993; Mooney, 2000).

Song system neurons exhibit some of the most selective sensory responses yet described. Many HVC neurons are 'BOS selective,' firing vigorously to BOS playback but not to playback of conspecific songs or time-reversed BOS (Figure 10) (Margoliash,

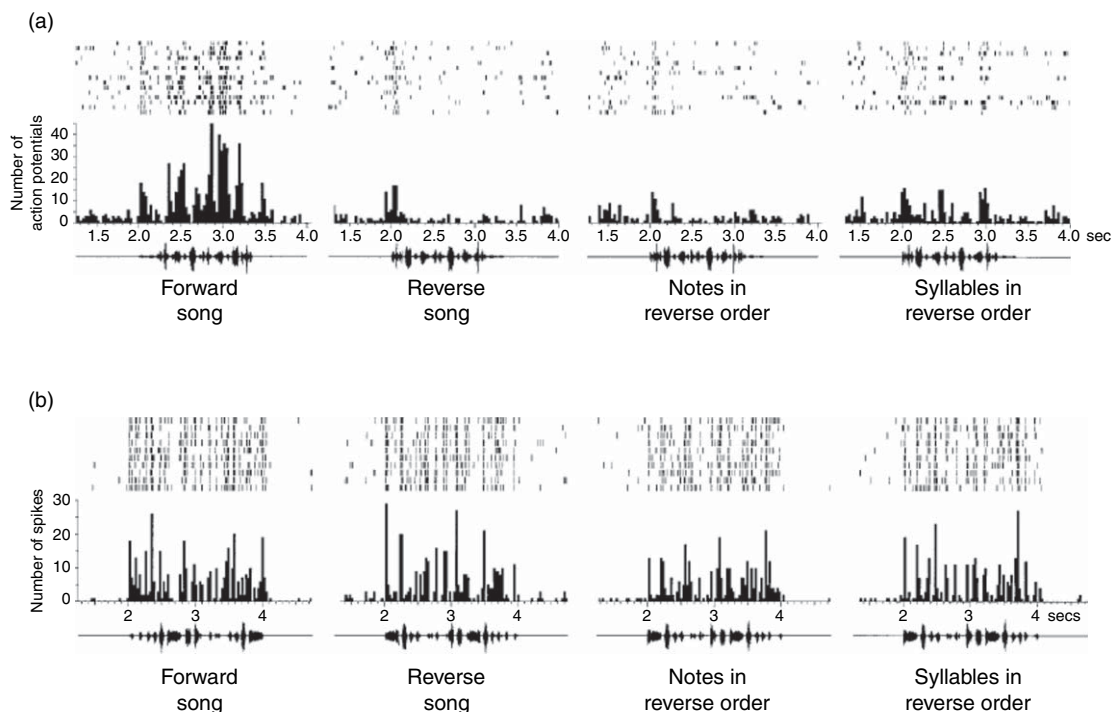


Figure 10 Auditory selectivity for the bird's own song (BOS) emerges between Field L and HVC. Each panel contains the raster of a single neuron's action potential response to the given auditory stimulus (top), the cumulative histogram of those responses (middle), and an oscillogram of the stimulus (bottom). (a) An HVC neuron responds strongly to playback of the BOS but weakly or not at all to temporally manipulated versions of the BOS. (b) In contrast, a Field L neuron responds strongly to playback of the BOS and to temporally manipulated versions of the BOS. Reprinted from Lewicki MS and Arthur BJ (1996) Hierarchical organization of auditory temporal context sensitivity. *J. Neurosci.* 16: 6987–6998.

1983, 1986; Doupe and Konishi, 1991; Volman, 1996). BOS-selective neurons are sensitive to temporal cues, as revealed by their selectivity for forward over reverse BOS, two stimuli with equivalent spectral content but contrasting temporal features. Some BOS-selective neurons also are sensitive to harmonic features of song (Margoliash and Fortune, 1992). Studies using synthetic songs have found that HVC neurons typically are more sensitive to degradation of temporal rather than spectral features, and that their temporal acuity is remarkable given HVC's distance from the auditory periphery (Theunissen and Doupe, 1998). Furthermore, a subset of HVC neurons responds exclusively to note-combinations in the BOS; studies where internote intervals were artificially manipulated show that these combination-sensitive neurons can integrate auditory information over hundreds of milliseconds (Margoliash, 1983; Lewicki and Konishi, 1995). Finally, in the swamp sparrow, a bird with multiple song types, different HVC neurons respond in an all-or-none fashion to different song types in the bird's repertoire (Mooney et al., 2001). From a functional standpoint, BOS-selective neurons are well suited for a feedback role, because they can respond differentially to slight variations in local (i.e., within-note) and global (i.e., note or syllable sequence) temporal structure of the BOS. BOS-selective neurons also could play an important communicative role by facilitating discrimination of the fine syntax variations that distinguish songs produced by conspecific birds from different breeding populations.

One clue that auditory activity in the song system actually plays a perceptual role is that lesions made either in HVC or in the AFP impair song recognition (Brenowitz, 1991; Scharff et al., 1998b; Burt et al., 2000). This perceptual deficit is perhaps most striking in female songbirds, which typically do not respond to playback of other species' (i.e., heterospecific) songs. However, following bilateral HVC lesions, females generate 'promiscuous' CSDs in response to heterospecific song playback (Brenowitz, 1991). In male songbirds, deficits in discrimination following lesions to the AFP are most pronounced for songs resembling the BOS, implicating BOS-selective neurons in perceptual processes (Scharff et al., 1998b). More generally, the mixed sensorimotor roles of HVC are strongly reminiscent of the mixed expressive and receptive roles in human speech served by language cortices in humans.

Another clue that auditory activity in the song system serves an important function is that it can be gated in a state-dependent fashion (Dave et al., 1998; Schmidt and Konishi, 1998). In the adult zebra finch,

playback-evoked auditory responses in NIf, HVC, and RA are most robust when the bird is asleep or anesthetized and diminished and more variable (but not altogether absent) during wakefulness (Dave et al., 1998; Schmidt and Konishi, 1998; Cardin and Schmidt, 2003, 2004). One idea is that sleep-wake changes in auditory activity in the song system reflect the presence of an auditory 'gate' that operates more dynamically in the waking bird as a function of arousal or changes in attention or saliency. Although the function of auditory gating in the song system is unknown, one idea is that it prevents auditory signals from altering vocal activity in sensorimotor neurons (Williams, 1989; Konishi, 2004). Additionally, auditory gating in HVC also may vary in a species-dependent manner; in notable contrast to the zebra finch, robust auditory activity is present in the HVC of both canaries and swamp sparrows during periods of wakefulness (McCasland and Konishi, 1981; Prather et al., in revision). In contrast to male zebra finches, which are colonial animals that sing unidirectionally to females, male canaries and sparrows are solitary animals that rely on song to identify neighboring males and defend territory, behaviors that may necessitate a more active role for the song system in auditory perception.

3.23.5.5.3 Sources of auditory input to the song system

The mechanisms that generate BOS electivity must to some extent be influenced by auditory experience, because the BOS is a learned behavior. Thus, locating where BOS selectivity arises in the brain can point to sites that encode aspects of auditory experience, particularly singing-related auditory feedback. Notably, BOS selectivity is largely absent from Field L, the avian equivalent of the mammalian primary auditory cortex, and the indirect source of auditory input to HVC (Figure 10) (Lewicki and Arthur, 1996; Amin et al., 2004; Theunissen et al., 2004). Current evidence indicates that BOS selectivity arises in areas interposed between Field L and HVC (Theunissen et al., 2004; Theunissen and Shaevitz, 2006) and that HVC integrates both selective and nonselective inputs from a variety of sources in the forebrain (Cardin and Schmidt, 2004; Coleman and Mooney, 2004; Rosen and Mooney, 2006; R. Mooney, unpublished observations).

Anatomical and functional studies indicate that HVC receives auditory inputs from three other song nuclei – NIf, Uva, and mMAN – and from the secondary auditory telencephalic region CM (Vates et al., 1997; Cardin and Schmidt, 2004; Coleman and

Mooney, 2004; R. Mooney, unpublished observations). At the population level, Nif and mMAN neurons are BOS selective, whereas Uva neurons are nonselective (Vates et al., 1997; Coleman and Mooney, 2004; M. Coleman personal communication). Similar to HVC, these three song nuclei are sensorimotor structures, and thus selectivity in these areas may reflect aspects of motor as well as auditory experience. In contrast, CM is embedded in the auditory telencephalon and thus may constitute a 'pure' source of auditory information to the song system. CM is densely interconnected with primary and secondary regions of the auditory telencephalon, including Field L and NCM (Vates et al., 1996). At the population level, CM neurons are not BOS selective, although they respond more to conspecific songs than to synthetic sounds, and their sensitivity to conspecific songs is enhanced relative to Field L neurons (Grace et al., 2003; Theunissen et al., 2004; Theunissen and Shaevitz, 2006). An especially fascinating study in starlings showed that the response properties of CM neurons can be altered during auditory learning tasks (Gentner and Margoliash, 2003). Furthermore, some CM neurons are BOS selective, and robust auditory activity can be detected in CM during quiet wakefulness and singing (R. Mooney, unpublished observations). Thus, CM may convey auditory feedback to the song system and could weight this information as a function of the bird's auditory experience of its own song and the songs of other birds.

Although a response bias to the BOS is established at least as early as Nif and in some CM neurons, cells in both areas show elevated firing rate responses to a wide range of non-BOS stimuli (Coleman and Mooney, 2004; R. Mooney, unpublished observations). In contrast, note combination-sensitive HVC neurons appear to fire only to the BOS and to the songs of conspecific birds with similar note sequences (Margoliash, 1983; Lewicki and Konishi, 1995). This all-or-none selectivity arises in HVC through synaptic interactions between HVC's BOS-selective excitatory afferents (i.e., Nif and possibly CM) and BOS-selective inhibitory interneurons in HVC (Mooney, 2000; Rosen and Mooney, 2003, 2006). Specifically, excitatory and inhibitory inputs onto HVC_X neurons generate highly nonlinear responses to the BOS through both thresholding effects and priming mechanisms (Rosen and Mooney, 2003). Thus, auditory representations of the BOS are enhanced locally in HVC, and both HVC and areas

immediately presynaptic to HVC are likely to encode aspects of auditory experience.

3.23.5.5.4 Does auditory activity in the song system encode the template?

In the context of a template model, one idea is that auditory activity in the song system encodes experience of the tutor song. In fact, studies in juvenile zebra finches found that blocking NMDA receptors in LMAN during tutoring sessions subsequently impaired copying (Basham et al., 1996). One potential confound is the close overlap between sensory acquisition and sensorimotor learning in zebra finches, which makes it difficult to rule out an effect of drug treatment on motor aspects of song learning. Another potential confound is a nonspecific impairment of attention or arousal, due perhaps to diffusion of the drug into brain regions surrounding LMAN.

A related idea is that auditory selectivity in the song system reflects experience of the tutor song. Nonetheless, several findings suggest that BOS selectivity reflects the bird's experience of its own song, rather than of its tutor. First, most HVC and AFP neurons in adult birds respond best to the BOS (Margoliash, 1986; Doupe and Konishi, 1991; Volman, 1996), whereas template neurons presumably would respond best to the tutor song. Second, juvenile zebra finches sequentially tutored by two different birds develop transient responses in LMAN to the first tutor's song and the bird's own imitation of this model, but these responses are lost or overwritten as the bird copies the second tutor (Yazaki-Sugiyama and Mooney, 2004). Thus, even when young birds demonstrate they have learned from a tutor, LMAN neurons do not permanently encode memories of these songs. Third, recordings made in HVC and the AFP of anesthetized juvenile songbirds reveal that song selectivity emerges only after the bird begins to sing; before this time, auditory responses in HVC and LMAN are typically weak and nonselective, despite experience of the tutor song sufficient to enable subsequent copying (Volman, 1993; Doupe, 1997). Moreover, in juvenile birds singing plastic song, most HVC and AFP neurons are BOS selective (Volman, 1993; Solis and Doupe, 1997), although many BOS-selective neurons also respond more strongly to the tutor song than to the songs of other conspecific birds (Solis and Doupe, 1997).

Neurons with 'dual selectivity' for the BOS and the tutor song could potentially encode tutor song experience, with the qualification that, when learning is successful, these two songs share acoustic features.

Thus, a potential caveat is that neurons in which selectivity was specified solely by the BOS might respond to these shared features, rather than encoding features unique to the tutor song. To investigate this possibility, Solis and Doupe unilaterally cut the syringeal nerve in juvenile zebra finches, spectrally distorting their songs and rendering them dissimilar from their tutors' songs based on several criteria (Solis and Doupe, 1999). Notably, most LMAN neurons in such 'dysphonic' juvenile birds developed strong selectivity for the distorted BOS, reinforcing the idea that the bird's experience of its own song is the primary factor influencing selectivity. Nonetheless, some neurons responded equally well to the distorted BOS and to the tutor song, raising the possibility that they encoded different BOS and tutor song features. However, the features in the distorted BOS and the tutor song that evoked responses were not characterized and were not necessarily those judged to be dissimilar in the two songs. Thus, it remains plausible that selectivity in LMAN is shaped by the bird's experience of its own song, and dual-selective neurons in 'dysphonic' birds respond to features common to the BOS and tutor song.

An important concern is that most studies of auditory selectivity in the song system have been conducted in anesthetized animals. Indeed, a recent study using chronic multiunit recordings in the awake juvenile zebra finch found evidence of mild selectivity for the tutor song in HVC (Nick and Konishi, 2005). Further studies are needed in freely behaving birds to confirm that auditory selectivity, as well as auditory responsiveness, may change in a state-dependent fashion. However, the present weight of evidence points away from the song system and the AFP in particular as sites where tutor song memories are stored.

These largely negative findings advance regions outside the song system as candidates for storing the song template (Bolhuis and Gahr, 2006). Foremost amongst these is NCM, which is reciprocally connected to CM and thus provides an indirect source of auditory input to the song system (Vates et al., 1996). Both IEG and electrophysiological studies show that auditory responses of NCM neurons habituate to repeated playback of the same song (Chew et al., 1995; Mello et al., 1995), consistent with NCM being a site of experience-dependent plasticity. A specific role for NCM in template storage is hinted at by the finding that tutor song playback can induce IEG expression in the adult zebra finch NCM, with expression levels correlating with how well the bird

copied the tutor song (Bolhuis et al., 2000, 2001; Terpstra et al., 2004). Similarly, NCM neuronal firing rates in adult finches habituate more slowly to playback of tutor song than to novel songs, with the slowest habituation rates for those tutor songs copied most accurately (Phan et al., 2006). As with studies of auditory selectivity in the song system, one necessary caveat is that these closely copied tutor songs are acoustically similar to the BOS. Thus, more definitive experiments, perhaps using vocal nerve section to increase the acoustical 'distance' between the BOS and the tutor song, are needed to determine to what extent NCM neurons encode tutor song memories as opposed to self-experience.

3.23.5.5.5 Does the song system process auditory feedback and/or error signals?

Singing-related auditory feedback is essential to sensorimotor learning and, in certain songbirds, to adult song maintenance. One idea is that feedback is evaluated by a neural comparator, which generates an error signal when it detects mismatches between the feedback signal and the template. The error signal could either provide 'simple' reinforcement, acting in an all-or-none fashion to 'punish' vocal errors (or to 'reward' correct performances), or provide information about the direction and magnitude of the vocal error. In either case, the error signal would adaptively modify song during sensorimotor learning, but it also could drive maladaptive changes, as when deafening or delayed feedback triggers song decrystallization. Although feedback must be integrated by the brain in real time as the bird sings, questions remain as to the timescale over which the resultant error signal operates. In an online model, auditory feedback acts over a short timescale (perhaps within a single song or song bout) to generate the error signal. In an offline model, the error signal arises more slowly, driving changes in song only after a substantial delay of hours, days, or even weeks.

The AFP is an attractive site to look for both auditory feedback and error signals because it conveys BOS-selective auditory information and because it is necessary to song plasticity. Anthony Leonardo directly tested whether the AFP in adult zebra finches encoded feedback or error signals by measuring the singing-related activity of individual LMAN neurons in the presence and absence of delayed auditory feedback (DAF), a treatment that decrystallizes song gradually over several weeks (Leonardo and Konishi, 1999; Leonardo, 2004). Notably, the singing-related activity patterns of

individual LMAN neurons were unchanged by DAF, at least over the relatively short timescales at which single-unit isolation could be maintained (tens of minutes) (Leonardo, 2004). This finding reinforced an earlier study, also performed in adult zebra finches, which found that singing-related multiunit activity patterns in LMAN were unaltered immediately after deafening (Hessler and Doupe, 1999a). These results are difficult to reconcile with a feedback function for the AFP, and instead show that most or all of the singing-related activity in the AFP is song motor corollary discharge. Indeed, the local HVC circuit contains direct and indirect synaptic pathways from HVC_{RA} to HVC_X neurons, providing a robust substrate for relaying song pre-motor activity to the AFP (Mooney and Prather, 2005). These findings also suggest that LMAN does not transmit an acute error signal but, instead, either conveys an offline error signal or plays a permissive rather than instructive role in song learning.

One technical limitation to these studies is that neural activity was monitored over only short timescales, whereas DAF and deafening induce song plasticity in adults only after many weeks (Nordeen and Nordeen, 1992; Leonardo and Konishi, 1999). The slow onset of adult plasticity raises the possibility that the 'gain' of feedback and/or error signals decreases markedly in the adult. One hint that feedback may act slowly in the adult AFP comes from the finding that, following syringeal nerve section in adult zebra finches, selectivity in LMAN can shift to the spectrally distorted song over a 1- to 2-week period, prior to the onset of decrystallization (Roy and Mooney, *in press*). Another hint that the AFP may convey an error signal over longer times is that auditory responses of LMAN neurons were absent in adult zebra finches that sustained syringeal nerve section as juveniles (Solis and Doupe, 2000); such depression of sensory-evoked activity could be caused by the actions of an error signal arising from the chronic mismatch between auditory feedback and the memorized model.

Another potential concern is that most attempts to detect feedback or error signals have been undertaken in the adult, because the crystallized song provides a stable motor 'background' on which to detect these signals. Nevertheless, feedback and error signals are likely to be most robust in juveniles singing plastic songs. Especially relevant in this regard are chronic recording studies in juvenile zebra finches, which report that short-term exposure to DAF failed to perturb singing-related activity of

HVC_X neurons (Kozhevnikov et al., 2006). Here an important consideration is that even in auditory-vocal specialists such as humans and bats, vocal modulation by auditory feedback is in some sense offline, arising only after a delay of 150 ms to several seconds following feedback perturbations (Schuller et al., 1975; Donath et al., 2002; Konishi, 2004). Thus examining activity patterns just during the motif may set too narrow a time window to detect feedback- or error signal-related signals.

Behavioral studies may highlight the best times during sensorimotor learning to search for error signals. In juvenile zebra finches, the most dynamic changes in song structure occur during the first few hours of the morning and overnight (Tchernichovski et al., 2001; Derégnaucourt et al., 2005). The rapid improvement in syllable matching seen each morning hints that online or fast offline processes adaptively modify song. Conversely, the nightly deterioration of the match between the BOS and the tutor song suggests that an offline error signal drives song deconsolidation during sleep. One plausible idea is that song deconsolidation is actively driven by a comparator that interprets bursting activity in HVC and RA during sleep as song motor activity lacking any sensory feedback (Dave and Margoliash, 2000; Derégnaucourt et al., 2005). The contrasting processes of daily improvement followed by nightly deconsolidation also underscore that song learning could involve multiple error signals, acting online as well as offline, rather than a single reinforcement or directional error signal acting entirely on- or offline.

3.23.6 Future Directions and Conclusions

Important insights into birdsong have been gleaned at many different levels, ranging from behavioral aspects of song learning to biomechanical and neural mechanisms of singing and song learning. Despite these important advances, some of the most basic and exciting questions remain to be answered, and comparative approaches remain vastly underexploited.

To date, the search for neural correlates of song has largely been a top-down affair. Consequently, we know much more about singing-related activity of neurons in HVC, RA, and LMAN than in the brainstem. It is unlikely that song motor codes can be fully deciphered without analyzing brainstem and

neuromuscular components of the song system in singing birds. Moreover, we still know remarkably little about coding strategies in the HVC and RA of species with larger and syntactically more variable repertoires than displayed by the zebra finch. To what extent is the sparse singing-related activity seen in the zebra finch HVC_{RA} neurons a general song-coding strategy, especially in species with large song repertoires? What are the mechanisms that generate variations in syntax that characterize songs of species other than the zebra finch? What are the mechanisms contributing to the remarkably sparse singing-related activity seen in HVC_{RA} neurons?

An especially important line of future research pertains to the synaptic basis of song learning. Notably, acute forms of synaptic plasticity have been detected in the AFP, and consolidation has been observed at HVC > RA synapses over development (Kittelberger and Mooney, 1999; Boettiger and Doupe, 2001; Ding and Perkel, 2004). Moreover, the architecture of the AFP suggests that RA is a major site of synaptic modification underlying song learning. However, whether classical forms of synaptic plasticity, such as LTP, contribute to song learning remains unknown, and the field is still in its infancy as far as relating synaptic and cellular mechanisms to the song behavior.

Arguably the most exciting questions in songbird research – the nature of the template, auditory feedback, and error signals – are still largely unanswered. The current body of largely negative evidence indicates that feedback or error signals arise in the song system of the adult only over a slow timescale or are mediated largely outside the song system. Nevertheless, concerns remain that we have not focused on the most appropriate species, employed the best methods for triggering an error signal, or concentrated on the right time during development. First, it may be useful to focus on those species, such as the Bengalese finch, that in adulthood depend acutely on auditory feedback to maintain their songs. Second, though DAF ultimately triggers song plasticity, initial exposure may not be detected by the bird as vocal error. Thus it may be useful to induce actual vocal errors, perhaps by stimulating the syringeal nerve during singing. Although technically challenging, more chronic recording studies are needed in juvenile birds learning to sing. The search for singing-related auditory feedback signals should be expanded to include those regions of auditory forebrain that ultimately provide auditory drive to the song system. Such a bottom-up approach may reveal the degree to which vocalization gates auditory activity in the

auditory system, as has been seen in other vocalizing animals, and help establish the degree to which these auditory areas can register changes in feedback in an online fashion. Finally, the nightly process of song deconsolidation seen during sensorimotor learning and the evidence of song motor replay seen in sleeping birds have lent support to the idea that these sleep-related patterns of activity are necessary to song learning. Therefore, a future goal should be to directly test whether spontaneous bursting activity in the sleeping bird plays a role in song learning.

References

- Akutagawa E and Konishi M (1998) Transient expression and transport of brain-derived neurotrophic factor in the male zebra finch's song system during vocal development. *Proc. Natl. Acad. Sci. USA* 95: 11429–11434.
- Amin N, Grace JA, and Theunissen FE (2004) Neural response to bird's own song and tutor song in the zebra finch field L and caudal mesopallium. *J. Comp. Physiol. A Neuroethol. Sens. Neural. Behav. Physiol.* 190: 469–489.
- Ashmore RC, Wild JM, and Schmidt MF (2005) Brainstem and forebrain contributions to the generation of learned motor behaviors for song. *J. Neurosci.* 25: 8543–8554.
- Ballentine B, Hyman J, and Nowicki S (2004) Vocal performance influences female response to male bird song: An experimental test. *Behav. Ecol.* 15: 163–168.
- Baptista LF and Petrinovich L (1984) Social interaction, sensitive phases and the song template hypothesis in the white-crowned sparrow. *Anim. Behav.* 32: 172–181.
- Baptista LF and Petrinovich L (1986) Song development in the white-crowned sparrow: Social factors and sex differences. *Anim. Behav.* 34: 1359–1371.
- Basham ME, Nordeen EJ, and Nordeen KW (1996) Blockade of NMDA receptors in the anterior forebrain impairs sensory acquisition in the zebra finch (*Poephila guttata*). *Neurobiol. Learn. Mem.* 66: 295–304.
- Beckers GJ, Suthers RA, and ten Cate C (2003) Pure-tone birdsong by resonance filtering of harmonic overtones. *Proc. Natl. Acad. Sci. USA* 100: 7372–7376.
- Benton S, Nelson DA, Marler P, and DeVogd TJ (1998) Anterior forebrain pathway is needed for stable song expression in adult male white-crowned sparrows (*Zonotrichia leucophrys*). *Behav. Brain Res.* 96: 135–150.
- Boettiger CA and Doupe AJ (1998) Intrinsic and thalamic excitatory inputs onto songbird LMAN neurons differ in their pharmacological and temporal properties. *J. Neurophysiol.* 79: 2615–2628.
- Boettiger CA and Doupe AJ (2001) Developmentally restricted synaptic plasticity in a songbird nucleus required for song learning. *Neuron* 31: 809–818.
- Bohner J (1990) Early acquisition of song in the zebra finch, *Taeniopygia guttata*. *Anim. Behav.* 39: 369–374.
- Bolhuis JJ and Gahr M (2006) Neural mechanisms of birdsong memory. *Nat. Rev. Neurosci.* 7: 347–357.
- Bolhuis JJ, Hetebrij E, Den Boer-Visser AM, De Groot JH, and Zijlstra GG (2001) Localized immediate early gene expression related to the strength of song learning in socially reared zebra finches. *Eur. J. Neurosci.* 13: 2165–2170.
- Bolhuis JJ, Zijlstra GG, den Boer-Visser AM, and Van Der Zee EA (2000) Localized neuronal activation in the zebra finch

- brain is related to the strength of song learning. *Proc. Natl. Acad. Sci. USA* 97: 2282–2285.
- Bottjer SW, Miesner EA, and Arnold AP (1984) Forebrain lesions disrupt development but not maintenance of song in passerine birds. *Science* 224: 901–903.
- Brainard M and Doupe A (2000) Interruption of a forebrain-basal ganglia circuit prevents plasticity of learned vocalizations. *Nature* 404: 762–766.
- Brenowitz EA (1991) Altered perception of species-specific song by female birds after lesions of a forebrain nucleus. *Science* 251: 303–305.
- Brenowitz EA (2004) Plasticity of the adult avian song control system. *Ann. N.Y. Acad. Sci.* 1016: 560–585.
- Brenowitz EA, Arnold AP, and Levin RN (1985) Neural correlates of female song in tropical duetting birds. *Brain Res.* 343: 104–112.
- Burt JM, Lent KL, Beecher MD, and Brenowitz EA (2000) Lesions of the anterior forebrain song control pathway in female canaries affect song perception in an operant task. *J. Neurobiol.* 42: 1–13.
- Canady RA, Burd GD, DeVogd TJ, and Nottebohm F (1988) Effect of testosterone on input received by an identified neuron type of the canary song system: A Golgi/electron microscopy/degeneration study. *J. Neurosci.* 8: 3770–3784.
- Cardin JA and Schmidt MF (2003) Song system auditory responses are stable and highly tuned during sedation, rapidly modulated and unselective during wakefulness, and suppressed by arousal. *J. Neurophysiol.* 90: 2884–2899.
- Cardin JA and Schmidt MF (2004) Auditory responses in multiple sensorimotor song system nuclei are co-modulated by behavioral state. *J. Neurophysiol.* 91: 2148–2163.
- Casey RM and Gaunt AS (1985) Theoretical models of the avian syrinx. *J. Theor. Biol.* 116: 45–64.
- Catchpole C and Slater P (1995) *Bird Song: Biological Themes and Variations*. Cambridge: Cambridge University Press.
- Chew SJ, Mello C, Nottebohm F, Jarvis E, and Vicario DS (1995) Decrements in auditory responses to a repeated conspecific song are long-lasting and require two periods of protein synthesis in the songbird forebrain. *Proc. Natl. Acad. Sci. USA* 92: 3406–3410.
- Clayton N and Prove E (1989) Song discrimination in female zebra finches and Bengalese finches. *Anim. Behav.* 38: 352–354.
- Coleman MJ and Mooney R (2004) Synaptic transformations underlying highly selective auditory representations of learned birdsong. *J. Neurosci.* 24: 7251–7265.
- Cowie R and Douglas-Cowie E (1992) *Postlingually Acquired Deafness: Speech Deterioration and the Wider Consequences*. Berlin: Mouton de Gruyter.
- Dale N and Roberts A (1984) Excitatory amino acid receptors in *Xenopus* embryo spinal cord and their role in the activation of swimming. *J. Physiol.* 348: 527–543.
- Dave A and Margoliash D (2000) Song replay during sleep and computational rules for sensorimotor vocal learning. *Science* 290: 812–816.
- Dave AS, Yu AC, and Margoliash D (1998) Behavioral state modulation of auditory activity in a vocal motor system. *Science* 282: 2250–2254.
- Del Negro C, Gahr M, Leboucher G, and Kreutzer M (1998) The selectivity of sexual responses to song displays: Effects of partial chemical lesion of the HVC in female canaries. *Behav. Brain Res.* 96: 151–159.
- Deregnacourt S, Mitra PP, Feher O, Pytte C, and Tchernichovski O (2005) How sleep affects the developmental learning of bird song. *Nature* 433: 710–716.
- DeVoogd TJ and Nottebohm F (1981) Sex differences in dendritic morphology of a song control nucleus in the canary: A quantitative Golgi study. *J. Comp. Neurol.* 196: 309–316.
- Ding L and Perkel DJ (2002) Dopamine modulates excitability of spiny neurons in the avian basal ganglia. *J. Neurosci.* 22: 5210–5218.
- Ding L and Perkel DJ (2004) Long-term potentiation in an avian basal ganglia nucleus essential for vocal learning. *J. Neurosci.* 24: 488–494.
- Donath TM, Natke U, and Kalveram KT (2002) Effects of frequency-shifted auditory feedback on voice F0 contours in syllables. *J. Acoust. Soc. Am.* 111: 357–366.
- Doupe AJ (1997) Song- and order-selective neurons in the songbird anterior forebrain and their emergence during vocal development. *J. Neurosci.* 17: 1147–1167.
- Doupe AJ and Konishi M (1991) Song-selective auditory circuits in the vocal control system of the zebra finch. *Proc. Natl. Acad. Sci. USA* 88: 11339–11343.
- Doupe A and Kuhl P (1999) Birdsong and human speech: Common themes and mechanisms. *Annu. Rev. Neurosci.* 22: 567–631.
- Doupe AJ, Perkel DJ, Reiner A, and Stern EA (2005) Birdbrains could teach basal ganglia research a new song. *Trends Neurosci.* 28: 353–363.
- Dye J, Heiligenberg W, Keller CH, and Kawasaki M (1989) Different classes of glutamate receptors mediate distinct behaviors in a single brainstem nucleus. *Proc. Natl. Acad. Sci. USA* 86: 8993–8997.
- Eales LA (1985) Song learning in zebra finches: Some effects of song model availability on what is learnt and when. *Anim. Behav.* 33: 1293–1300.
- Eales LA (1987) Song learning in female-raised zebra finches: Another look at the sensitive phase. *Anim. Behav.* 35: 1356–1365.
- Farries MA and Perkel DJ (2002) A telencephalic nucleus essential for song learning contains neurons with physiological characteristics of both striatum and globus pallidus. *J. Neurosci.* 22: 3776–3787.
- Fee MS, Kozhevnikov AA, and Hahnloser RH (2004) Neural mechanisms of vocal sequence generation in the songbird. *Ann. N.Y. Acad. Sci.* 1016: 153–170.
- Fee MS, Shraiman B, Pesaran B, and Mitra PP (1998) The role of nonlinear dynamics of the syrinx in the vocalizations of a songbird. *Nature* 395: 67–71.
- Fiete IR, Hahnloser RH, Fee MS, and Seung HS (2004) Temporal sparseness of the premotor drive is important for rapid learning in a neural network model of birdsong. *J. Neurophysiol.* 92: 2274–2282.
- Fletcher NH, Riede T, and Suthers RA (2006) Model for vocalization by a bird with distensible vocal cavity and open beak. *J. Acoust. Soc. Am.* 119: 1005–1011.
- Fortune ES and Margoliash D (1995) Parallel pathways and convergence onto HVC and adjacent neostriatum of adult zebra finches (*Taeniopygia guttata*). *J. Comp. Neurol.* 360: 413–441.
- Foster EF and Bottjer SW (1998) Axonal connections of the high vocal center and surrounding cortical regions in juvenile and adult male zebra finches. *J. Comp. Neurol.* 397: 118–138.
- Franz M and Goller F (2002) Respiratory units of motor production and song imitation in the zebra finch. *J. Neurobiol.* 51: 129–141.
- Funabiki Y and Konishi M (2003) Long memory in song learning by zebra finches. *J. Neurosci.* 23: 6928–6935.
- Gardner TJ, Naef F, and Nottebohm F (2005) Freedom and rules: The acquisition and reprogramming of a bird's learned song. *Science* 308: 1046–1049.
- Gaunt AS (1983) An hypothesis concerning the relationship of syringeal structure to vocal abilities. *Auk* 100: 853–862.
- Gaunt AS, Gaunt SL, and Casey RM (1982) Syringeal mechanics reassessed: Evidence from *Streptopelia*. *Auk* 99: 474–494.
- Gentner TQ and Margoliash D (2003) Neuronal populations and single cells representing learned auditory objects. *Nature* 424: 669–674.

- Glaze CM and Troyer TW (2006) Temporal structure in zebra finch song: Implications for motor coding. *J. Neurosci.* 26: 991–1005.
- Goller F and Cooper BG (2004) Peripheral motor dynamics of song production in the zebra finch. *Ann. N.Y. Acad. Sci.* 1016: 130–152.
- Goller F and Larsen ON (1997) A new mechanism of sound generation in songbirds. *Proc. Natl. Acad. Sci. USA* 94: 14787–14791.
- Goller F, Mallinckrodt MJ, and Torti SD (2004) Beak gape dynamics during song in the zebra finch. *J. Neurobiol.* 59: 289–303.
- Goller F and Suthers R (1995) Implications for lateralization of bird song from unilateral gating of bilateral motor patterns. *Nature* 373: 63–66.
- Goller F and Suthers R (1996a) Role of syringeal muscles in controlling the phonology of bird song. *J. Neurophysiol.* 76: 287–300.
- Goller F and Suthers R (1996b) Role of syringeal muscles in gating airflow and sound production in singing brown thrashers. *J. Neurophysiol.* 75: 867–876.
- Grace JA, Amin N, Singh NC, and Theunissen FE (2003) Selectivity for conspecific song in the zebra finch auditory forebrain. *J. Neurophysiol.* 89: 472–487.
- Greenwalt CH (1968) *Birdsong: Acoustics and Physiology*. Washington DC: Smithsonian University Press.
- Hahnloser RH, Kozhevnikov AA, and Fee MS (2002) An ultra-sparse code underlies the generation of neural sequences in a songbird. *Nature* 419: 65–70.
- Hartley RS and Suthers RA (1990) Lateralization of syringeal function during song production in the canary. *J. Neurobiol.* 21: 1236–1248.
- Herrmann K and Arnold AP (1991) The development of afferent projections to the robust archistriatal nucleus in male zebra finches: A quantitative electron microscopic study. *J. Neurosci.* 11: 2063–2074.
- Hessler NA and Doupe AJ (1999a) Singing-related neural activity in a dorsal forebrain-basal ganglia circuit of adult zebra finches. *J. Neurosci.* 19: 10461–10481.
- Hessler NA and Doupe AJ (1999b) Social context modulates singing-related neural activity in the songbird forebrain. *Nat. Neurosci.* 2: 209–211.
- Hultsch H and Todt D (1989a) Memorization and reproduction of songs in nightingales (*Luscinia megarhynchos*): Evidence for package formation. *J. Comp. Physiol. A* 165: 197–203.
- Hultsch H and Todt D (1989b) Song acquisition and acquisition constraints in nightingale (*Luscinia megarhynchos*). *Naturwissenschaften* 76: 83–86.
- Immelmann K (1969) Song development in zebra finch and other Estrildid finches. In: Hinde RA (ed.) *Bird Vocalisations*, pp. 61–74. London: Cambridge University Press.
- Jarvis ED, Scharff C, Grossman MR, Ramos JA, and Nottebohm F (1998) For whom the bird sings: Context dependent gene expression. *Neuron* 21: 775–788.
- Johnson F, Hohmann SE, DiStefano PS, and Bottjer SW (1997) Neurotrophins suppress apoptosis induced by deafferentation of an avian motor-cortical region. *J. Neurosci.* 17: 2101–2111.
- Kao MH and Brainard MS (2006) Lesions of an avian basal ganglia circuit prevent context-dependent changes to song variability. *J. Neurophysiol.* 96: 1441–1455.
- Kao MH, Doupe AJ, and Brainard MS (2005) Contributions of an avian basal ganglia-forebrain circuit to real-time modulation of song. *Nature* 433: 638–643.
- Katz LC and Gurney ME (1981) Auditory responses in the zebra finch's motor system for song. *Brain Res.* 221: 192–197.
- King AS (1979) Functional anatomy of the syrinx. In: King AS and McLelland J (eds.) *Form and Function in Birds*, pp. 105–192. London: Academic Press.
- Kirn JR, Alvarez-Buylla A, and Nottebohm F (1991) Production and survival of projection neurons in a forebrain vocal center of adult male canaries. *J. Neurosci.* 11: 1756–1762.
- Kittelberger J and Mooney R (1999) Lesions of an avian forebrain nucleus that disrupt song development alter synaptic connectivity and transmission in the vocal premotor pathway. *J. Neurosci.* 19: 9385–9398.
- Kittelberger JM and Mooney R (2005) Acute injections of brain-derived neurotrophic factor in a vocal premotor nucleus reversibly disrupt adult birdsong stability and trigger syllable deletion. *J. Neurobiol.* 62: 406–424.
- Konishi M (1965) The role of auditory feedback in the control of vocalization in the white-crowned sparrow. *Z. Tierpsychol.* 22: 770–783.
- Konishi M (2004) The role of auditory feedback in birdsong. *Ann. N.Y. Acad. Sci.* 1016: 463–475.
- Konishi M and Nottebohm F (1969) Experimental studies in the ontogeny of avian vocalizations. In: Hinde RA (ed.) *Bird Vocalizations*, pp. 29–48. Cambridge: Cambridge University Press.
- Korsia S and Bottjer SW (1991) Chronic testosterone treatment impairs vocal learning in male zebra finches during a restricted period of development. *J. Neurosci.* 11: 2362–2371.
- Kozhevnikov A and Fee M (2006) Singing-related activity of identified HVC neurons in the zebra finch. *J. Neurophysiol.* December 20 published ahead of print.
- Krebs JR (1977) Song and territory in the great tit *Parus major*. In: Stonehouse B and Perrins CM (eds.) *Evolutionary Ecology*, pp. 47–62. New York: MacMillan.
- Kroodsma D and Konishi M (1991) A suboscine bird (eastern phoebe, *Sayornis phoebe*) develops normal song without auditory feedback. *Anim. Behav.* 42: 477–484.
- Kubke MF, Yazaki-Sugiyama Y, Mooney R, and Wild JM (2005) Physiology of neuronal subtypes in the respiratory-vocal integration nucleus retroamigualis of the male zebra finch. *J. Neurophysiol.* 94: 2379–2390.
- Kubota M and Saito N (1991) NMDA receptors participate differentially in two different synaptic inputs in neurons of the zebra finch robust nucleus of the archistriatum *in vitro*. *Neurosci. Lett.* 125: 107–109.
- Langmore NE (1998) Functions of duet and solo songs of female birds. *Trends Ecol. Evol.* 13: 136–140.
- Larsen ON and Goller F (2002) Direct observation of syringeal muscle function in songbirds and a parrot. *J. Exp. Biol.* 205: 25–35.
- Leonardo A (2004) Experimental test of the birdsong error-correction model. *Proc. Natl. Acad. Sci. USA* 101: 16935–16940.
- Leonardo A and Fee MS (2005) Ensemble coding of vocal control in birdsong. *J. Neurosci.* 25: 652–661.
- Leonardo A and Konishi M (1999) Decrystallization of adult birdsong by perturbation of auditory feedback. *Nature* 399: 466–470.
- Lewicki MS and Arthur BJ (1996) Hierarchical organization of auditory temporal context sensitivity. *J. Neurosci.* 16: 6987–6998.
- Lewicki MS and Konishi M (1995) Mechanisms underlying the sensitivity of songbird forebrain neurons to temporal order. *Proc. Natl. Acad. Sci. USA* 92: 5582–5586.
- Li XC, Jarvis ED, Alvarez-Borda B, Lim DA, and Nottebohm F (2000) A relationship between behavior, neurotrophin expression, and new neuron survival. *Proc. Natl. Acad. Sci. USA* 97: 8584–8589.
- Livingston FS and Mooney R (1997) Development of intrinsic and synaptic properties in a forebrain nucleus essential to avian song learning. *J. Neurosci.* 17: 8997–9009.
- Livingston F, White S, and Mooney R (2000) Slow NMDA-EPSCs at synapses critical for song development are not

- required for song learning in zebra finches. *Nat. Neurosci.* 3: 482–488.
- Luo M and Perkel DJ (1999) A GABAergic, strongly inhibitory projection to a thalamic nucleus in the zebra finch song system. *J. Neurosci.* 19: 6700–6711.
- Manogue KR and Paton JA (1982) Respiratory gating of activity in the avian vocal control system. *Brain Res.* 247: 383–387.
- Margoliash D (1983) Acoustic parameters underlying the responses of song-specific neurons in the white-crowned sparrow. *J. Neurosci.* 3: 1039–1057.
- Margoliash D (1986) Preference for autogenous song by auditory neurons in a song system nucleus of the white-crowned sparrow. *J. Neurosci.* 6: 1643–1661.
- Margoliash D and Fortune ES (1992) Temporal and harmonic combination-sensitive neurons in the zebra finch's HVC. *J. Neurosci.* 12: 4309–4326.
- Margoliash D and Konishi M (1985) Auditory representation of autogenous song in the song system of white-crowned sparrows. *Proc. Natl. Acad. Sci. USA* 82: 5997–6000.
- Marler P (1970) A comparative approach to vocal learning: Song development in white-crowned sparrows. *J. Comp. Physiol. Psychol. Monogr.* 71: 1–25.
- Marler P (1990) Innate learning preferences-signals for communication. *Dev. Psychobiol.* 23: 557–568.
- Marler P (2004a) Science and birdsong: The good old days. In: Marler P and Slabbekoorn H (eds.) *Nature's Music: The Science of Birdsong*, pp. 1–37. London: Elsevier Academic Press.
- Marler P (2004b) Bird Calls: A cornucopia for communication. In: Marler P and Slabbekoorn H (eds.) *Nature's Music: The Science of Birdsong*, pp. 132–176. London: Elsevier Academic Press.
- Marler P and Peters S (1981) Sparrows learn adult song and more from memory. *Science* 213: 780–782.
- Marler P and Peters S (1982a) Structural changes in song ontogeny in the swamp sparrow *Melospiza georgiana*. *Auk* 99: 446–458.
- Marler P and Peters S (1982b) Long-term storage of learned birdsongs prior to production. *Anim. Behav.* 30: 479–482.
- Marler P and Peters S (1982c) Developmental overproduction and selective attrition: New processes in the epigenesis of birdsong. *Dev. Psychobiol.* 15: 369–378.
- Marler P and Peters S (1987) A sensitive period for song acquisition in the song sparrow, *Melospiza melodia*: A case of age-limited learning. *Ethology* 76: 89–100.
- Marler P and Peters S (1988) Sensitive periods for song acquisition from tape recordings and live tutors in the swamp sparrow *Melospiza georgiana*. *Ethology* 77: 76–84.
- Marler P and Peters S (1989) Species differences in auditory responsiveness in early vocal learning. In: Dooling RJ and Hulse SH (eds.) *The Comparative Psychology of Audition: Perceiving Complex Sounds*, pp. 243–273. Hillsdale, NJ: Lawrence Erlbaum.
- Marler P, Peters S, Ball GF, Duffy AM, Jr., and Wingfield JC (1988) The role of sex steroids in the acquisition and production of birdsong. *Nature* 336: 770–772.
- Marler P and Tamura M (1964) Culturally transmitted patterns of vocal behaviour in sparrows. *Science* 146: 1483–1486.
- McCasland JS and Konishi M (1981) Interaction between auditory and motor activities in an avian song control nucleus. *Proc. Natl. Acad. Sci. USA* 78: 7815–7819.
- McDonald MV (1989) Function of song in Scott's seaside sparrow *Ammodramus maritimus peninsulæ*. *Anim. Behav.* 38: 468–485.
- Mello C, Nottebohm F, and Clayton D (1995) Repeated exposure to one song leads to a rapid and persistent decline in an immediate early gene's response to that song in zebra finch telencephalon. *J. Neurosci.* 15: 6919–6925.
- Mindlin G (2005) *The Physics of Birdsong*. Berlin: Springer.
- Mindlin GB, Gardner TJ, Goller F, and Suthers R (2003) Experimental support for a model of birdsong production. *Phys. Rev. E Stat. Nonlin. Soft. Matter Phys.* 68: 041908.
- Miskimen M (1951) Sound production in passerine birds. *Auk* 68: 493–504.
- Mooney R (1992) Synaptic basis for developmental plasticity in a birdsong nucleus. *J. Neurosci.* 12: 2464–2477.
- Mooney R (2000) Different subthreshold mechanisms underlie song-selectivity in identified HVC neurons of the zebra finch. *J. Neurosci.* 20: 5420–5436.
- Mooney R, Hoese W, and Nowicki S (2001) Auditory representation of the vocal repertoire in a songbird with multiple song types. *Proc. Natl. Acad. Sci. USA* 98: 12778–12783.
- Mooney R and Konishi M (1991) Two distinct inputs to an avian song nucleus activate different glutamate receptor subtypes on individual neurons. *Proc. Natl. Acad. Sci. USA* 88: 4075–4079.
- Mooney R and Prather JF (2005) The HVC microcircuit: The synaptic basis for interactions between song motor and vocal plasticity pathways. *J. Neurosci.* 25: 1952–1964.
- Morrison RG and Nottebohm F (1993) Role of a telencephalic nucleus in the delayed song learning of socially isolated zebra finches. *J. Neurobiol.* 24: 1045–1064.
- Naguib M and Wiley H (2001) Review: Estimating the distance to a source of sound: Mechanisms and adaptations for long-range communication. *Anim. Behav.* 62: 825–837.
- Nelson BS, Beckers GJ, and Suthers RA (2005) Vocal tract filtering and sound radiation in a songbird. *J. Exp. Biol.* 208: 297–308.
- Nelson DA and Marler P (1989) Categorical perception of a natural stimulus continuum: Birdsong. *Science* 244: 976–978.
- Nelson DA and Marler P (1994) Selection-based learning in bird song development. *Proc. Natl. Acad. Sci. USA* 91: 10498–10501.
- Nick TA and Konishi M (2005) Neural song preference during vocal learning in the zebra finch depends on age and state. *J. Neurobiol.* 62: 231–242.
- Nixdorf-Bergweiler BE, Lips MB, and Heinemann U (1995) Electrophysiological and morphological evidence for a new projection of LMAN-neurons towards area X. *Neuroreport* 6: 1729–1732.
- Nordeen KW and Nordeen EJ (1992) Auditory feedback is necessary for the maintenance of stereotyped song in adult zebra finches. *Behav. Neural Biol.* 57: 58–66.
- Nottebohm F (1971) Neural lateralization of vocal control in a passerine bird. I. Song. *J. Exp. Zool.* 177: 229–261.
- Nottebohm F (1976) Phonation in the orange-winged Amazon parrot, *Amazona amazonica*. *J. Comp. Physiol.* 108: 157–170.
- Nottebohm F (1977) Asymmetries in neural control of vocalization in the canary. In: Harnad S (ed.) *Lateralization in the Nervous System*, pp. 23–44. New York: Academic Press.
- Nottebohm F (1981) A brain for all seasons: Cyclical anatomical changes in song control nuclei of the canary brain. *Science* 214: 1368–1370.
- Nottebohm F (1984) Birdsong as a model in which to study brain processes related to learning. *Condor* 86: 227–236.
- Nottebohm F (2005) The neural basis of birdsong. *PLoS Biol.* 3: e164.
- Nottebohm F and Arnold AP (1976) Sexual dimorphism in vocal control areas of the songbird brain. *Science* 194: 211–213.
- Nottebohm F, Kasparian S, and Pandazis C (1981) Brain space for a learned task. *Brain Res.* 213: 99–109.
- Nottebohm F, Kelley DB, and Paton JA (1982) Connections of vocal control nuclei in the canary telencephalon. *J. Comp. Neurol.* 207: 344–357.

- Nottebohm F and Nottebohm M (1978) Relationship between song repertoire and age in the canary. *Z. Tierpsychol.* 46: 298–305.
- Nottebohm F, Nottebohm ME, Crane LA, and Wingfield JC (1987) Seasonal changes in gonadal hormone levels of adult male canaries and their relation to song. *Behav. Neural Biol.* 47: 197–211.
- Nottebohm F, Stokes TM, and Leonard CM (1976) Central control of song in the canary, *Serinus Canarius*. *J. Comp. Neurol.* 165: 457–486.
- Nowicki S (1987) Vocal tract resonances in oscine bird sound production: Evidence from birdsongs in a helium atmosphere. *Nature* 325: 53–55.
- Okanoya K and Yamaguchi A (1997) Adult Bengalese finches (*Lonchura striata* var. *domestica*) require real-time auditory feedback to produce normal song syntax. *J. Neurobiol.* 33: 343–356.
- Okuhata S and Saito N (1987) Synaptic connections of a forebrain nucleus involved with vocal learning in zebra finches. *Brain Res. Bull.* 18: 35–44.
- Olveczky BP, Andalman AS, and Fee MS (2005) Vocal experimentation in the juvenile songbird requires a basal ganglia circuit. *PLoS Biol.* 3: e153.
- Person AL and Perkel DJ (2005) Unitary IPSPs drive precise thalamic spiking in a circuit required for learning. *Neuron* 46: 129–140.
- Phan ML, Pytte CL, and Vicario DS (2006) Early auditory experience generates long-lasting memories that may subserve vocal learning in songbirds. *Proc. Natl. Acad. Sci. USA* 103: 1088–1093.
- Price R (1979) Developmental determinants of structure in zebra finch song. *J. Comp. Physiol. Psychol.* 93: 268–277.
- Pytte CL and Suthers RA (2000) Sensitive period for sensorimotor integration during vocal motor learning. *J. Neurobiol.* 42: 172–189.
- Reinke H and Wild JM (1998a) Identification and connections of inspiratory premotor neurons in songbirds and budgerigar. *J. Comp. Neurol.* 391: 147–163.
- Reinke H and Wild J (1998b) Identification and connections of inspiratory premotor neurons in songbird and budgerigar. *J. Comp. Neurol.* 391: 147–163.
- Riede T, Suthers RA, Fletcher NH, and Blevins WE (2006) Songbirds tune their vocal tract to the fundamental frequency of their song. *Proc. Natl. Acad. Sci. USA* 103: 5543–5548.
- Rose GJ, Goller F, Gritton HJ, Plamondon SL, Baugh AT, and Cooper BG (2004) Species-typical songs in white-crowned sparrows tutored with only phrase pairs. *Nature* 432: 753–758.
- Rosen MJ and Mooney R (2003) Inhibitory and excitatory mechanisms underlying auditory responses to learned vocalizations in the songbird nucleus HVC. *Neuron* 39: 177–194.
- Rosen MJ and Mooney R (2006) Synaptic interactions underlying song-selectivity in the avian nucleus HVC revealed by dual intracellular recordings. *J. Neurophysiol.* 95: 1158–1175.
- Roy A and Mooney R (in press) Auditory plasticity in a basal ganglia-forebrain pathway during decrystallization of adult birdsong. *J. Neurosci.*
- Scharff C, Kirn JR, Grossman M, Macklis JD, and Nottebohm F (2000) Targeted neuronal death affects neuronal replacement and vocal behavior in adult songbirds [see comments]. *Neuron* 25: 481–492.
- Scharff C and Nottebohm F (1991) A comparative study of the behavioral deficits following lesions of various parts of the zebra finch song system: Implications for vocal learning. *J. Neurosci.* 11: 2896–2913.
- Scharff C, Nottebohm F, and Cynx J (1998a) Conspecific and heterospecific song discrimination in male zebra finches with lesions in the anterior forebrain pathway. *J. Neurobiol.* 36: 81–90.
- Scharff C, Nottebohm F, and Cynx J (1998b) Conspecific and heterospecific song discrimination in male zebra finches with lesions in the anterior forebrain pathway. *J. Neurobiol.* 36: 81–90.
- Scheid P and Piiper J (1979) Respiratory Mechanics and air flow in birds. In: King AS and McLelland J (eds.) *Form and Function in Birds*, pp. 369–391. San Diego: Academic Press.
- Schmidt MF and Konishi M (1998) Gating of auditory responses in the vocal control system of awake songbirds. *Nat. Neurosci.* 1: 513–518.
- Schuller G, Beuter K, and Rubsamen R (1975) Dynamic properties of the compensation system for Doppler-shifts in the bat *Rhinolophus Ferrumequinum*. *J. Comp. Physiol.* 114: 113–125.
- Scott LL, Singh TD, Nordeen EJ, and Nordeen KW (2004) Developmental patterns of NMDAR expression within the song system do not recur during adult vocal plasticity in zebra finches. *J. Neurobiol.* 58: 442–454.
- Searcy W and Brenowitz E (1988) Sexual differences in species recognition of avian song. *Nature* 332: 152–154.
- Searcy WA, Marler P, and Peters SS (1985) Songs of isolation-reared sparrows function in communication, but are significantly less effective than learned songs. *Behav. Ecol. Sociobiol.* 17: 223–229.
- Selverston AI and Moulins M (1985) Oscillatory neural networks. *Annu. Rev. Physiol.* 47: 29–48.
- Setherwall CG (1901) Studies öfver syrinx hos polymyoda passerer Ph.D. Dissertation, University of Lund.
- Simpson HB and Vicario DS (1990) Brain pathways for learned and unlearned vocalizations differ in zebra finches. *J. Neurosci.* 10: 1541–1556.
- Singh TD, Heinrich JE, Wissman AM, Brenowitz EA, Nordeen EJ, and Nordeen KW (2003) Seasonal regulation of NMDA receptor NR2B mRNA in the adult canary song system. *J. Neurobiol.* 54: 593–603.
- Smith GT, Brenowitz EA, and Wingfield JC (1997a) Roles of photoperiod and testosterone in seasonal plasticity of the avian song control system. *J. Neurobiol.* 32: 426–442.
- Smith GT, Brenowitz EA, Beecher MD, and Wingfield JC (1997b) Seasonal changes in testosterone, neural attributes of song control nuclei, and song structure in wild songbirds. *J. Neurosci.* 17: 6001–6010.
- Sohrabji F, Nordeen EJ, and Nordeen KW (1990) Selective impairment of song learning following lesions of a forebrain nucleus in the juvenile zebra finch. *Behav. Neural Biol.* 53: 51–63.
- Solis MM and Doupe AJ (1997) Anterior forebrain neurons develop selectivity by an intermediate stage of birdsong learning. *J. Neurosci.* 17: 6447–6462.
- Solis MM and Doupe AJ (1999) Contributions of tutor and bird's own song experience to neural selectivity in the songbird anterior forebrain. *J. Neurosci.* 19: 4559–4584.
- Solis MM and Doupe AJ (2000) Compromised neural selectivity for song in birds with impaired sensorimotor learning. *Neuron* 25: 109–121.
- Solis MM and Perkel DJ (2005) Rhythmic activity in a forebrain vocal control nucleus *in vitro*. *J. Neurosci.* 25: 2811–2822.
- Spiro J, Dalva M, and Mooney R (1999) Long-range inhibition within the zebra finch song nucleus RA can coordinate the firing of multiple projection neurons. *J. Neurophysiol.* 81: 3007–3020.
- Stark LL and Perkel DJ (1999) Two-stage, input-specific synaptic maturation in a nucleus essential for vocal production in the zebra finch. *J. Neurosci.* 19: 9107–9116.
- Striedter GF and Vu ET (1998) Bilateral feedback projections to the forebrain in the premotor network for singing in zebra finches. *J. Neurobiol.* 34: 27–40.
- Sturdy CB, Wild JM, and Mooney R (2003) Respiratory and telencephalic modulation of vocal motor neurons in the zebra finch. *J. Neurosci.* 23: 1072–1086.

- Suthers R (1990) Contributions to birdsong from the left and right sides of the intact syrinx. *Nature* 347: 473–477.
- Suthers RA, Goller F, and Hartley RS (1994) Motor dynamics of song production by mimic thrushes. *J. Neurobiol.* 25: 917–936.
- Suthers RA, Goller F, and Wild JM (2002) Somatosensory feedback modulates the respiratory motor program of crystallized birdsong. *Proc. Natl. Acad. Sci. USA* 99: 5680–5685.
- Suthers RA and Margoliash D (2002) Motor control of birdsong. *Curr. Opin. Neurobiol.* 12: 684–690.
- Suthers RA, Vallet E, Tanvez A, and Kreutzer M (2004) Bilateral song production in domestic canaries. *J. Neurobiol.* 60: 381–393.
- Suthers RA and Zollinger SA (2004) Producing song: The vocal apparatus. *Ann. N.Y. Acad. Sci.* 1016: 109–129.
- Tchernichovski O, Mitra PP, Lint-S T, and Nottebohm F (2001) Dynamics of the vocal imitation process: How a zebra finch learns its song. *Science* 291: 2564–2569.
- Tchernichovski O, Nottebohm F, Ho CE, Pesaran B, and Mitra PP (2000) A procedure for an automated measurement of song similarity. *Anim. Behav.* 59: 1167–1176.
- Terpstra NJ, Bolhuis JJ, and den Boer-Visser AM (2004) An analysis of the neural representation of birdsong memory. *J. Neurosci.* 24: 4971–4977.
- Theunissen FE, Amin N, Shaevitz SS, Woolley SM, Fremouw T, and Hauber ME (2004) Song selectivity in the song system and in the auditory forebrain. *Ann. N.Y. Acad. Sci.* 1016: 222–245.
- Theunissen FE and Doupe AJ (1998) Temporal and spectral sensitivity of complex auditory neurons in the nucleus HVC of male zebra finches. *J. Neurosci.* 18: 3786–3802.
- Theunissen FE and Shaevitz SS (2006) Auditory processing of vocal sounds in birds. *Curr. Opin. Neurobiol.* 16: 400–407.
- Thorpe W (1954) The process of song learning in the chaffinch as studied by means of the sound spectrograph. *Nature* 173: 465.
- Thorpe W (1958) The learning of song patterns by birds, with especial reference to the song of the chaffinch. *Ibis* 100: 535–570.
- Vates GE, Broome BM, Mello CV, and Nottebohm F (1996) Auditory pathways of caudal telencephalon and their relation to the song system of adult male zebra finches. *J. Comp. Neurol.* 366: 613–642.
- Vates GE, Vicario DS, and Nottebohm F (1997) Reafferent thalamo- “cortical” loops in the song system of oscine songbirds. *J. Comp. Neurol.* 380: 275–290.
- Vicario D (1991a) Contributions of syringeal muscles to respiration and vocalization in the zebra finch. *J. Neurobiol.* 2: 63–73.
- Vicario DS (1991b) Organization of the zebra finch song control system: II. Functional organization of outputs from nucleus Robustus archistriatalis. *J. Comp. Neurol.* 309: 486–494.
- Vicario DS and Nottebohm F (1988) Organization of the zebra finch song control system: I. Representation of syringeal muscles in the hypoglossal nucleus. *J. Comp. Neurol.* 271: 346–354.
- Vicario DS and Yohay KH (1993) Song-selective auditory input to a forebrain vocal control nucleus in the zebra finch. *J. Neurobiol.* 24: 488–505.
- Volman SF (1993) Development of neural selectivity for birdsong during vocal learning. *J. Neurosci.* 13: 4737–4747.
- Volman SF (1996) Quantitative assessment of song-selectivity in the zebra finch “high vocal center.” *J. Comp. Physiol. [A]* 178: 849–862.
- Vu ET, Mazurek ME, and Kuo YC (1994) Identification of a forebrain motor programming network for the learned song of zebra finches. *J. Neurosci.* 14: 6924–6934.
- Westneat MW, Long JH, Jr., Hoese W, and Nowicki S (1993) Kinematics of birdsong: Functional correlation of cranial movements and acoustic features in sparrows. *J. Exp. Biol.* 182: 147–171.
- White S, Livingston F, and Mooney R (1999) Androgens modulate NMDA receptor-mediated EPSCs in the zebra finch song system. *J. Neurophysiol.* 82: 2221–2234.
- Wild JM (1993a) The avian nucleus retroambiguus: A nucleus for breathing, singing and calling. *Brain Res.* 606: 319–324.
- Wild JM (1993b) Descending projections of the songbird nucleus robustus archistriatalis. *J. Comp. Neurol.* 338: 225–241.
- Wild JM (1994) The auditory-vocal-respiratory axis in birds. *Brain Behav. Evol.* 44: 192–209.
- Wild JM (1997a) Neural pathways for the control of birdsong production. *J. Neurobiol.* 33: 653–670.
- Wild JM (1997b) Neural pathways for the control of birdsong production. *J. Neurobiol.* 33: 653–670.
- Wild JM (2004) Functional neuroanatomy of the sensorimotor control of singing. *Ann. N.Y. Acad. Sci.* 1016: 438–462.
- Wild JM, Li D, and Eagleton C (1997) Projections of the dorsomedial nucleus of the intercollicular complex (DM) in relation to respiratory-vocal nuclei in the brainstem of pigeon (*Columba livia*) and zebra finch (*Taeniopygia guttata*). *J. Comp. Neurol.* 377: 392–413.
- Wild JM, Williams MN, and Suthers RA (2000) Neural pathways for bilateral vocal control in songbirds. *J. Comp. Neurol.* 423: 413–426.
- Williams H (1989) Multiple representations and auditory-motor interactions in the avian song system. *Ann. N.Y. Acad. Sci.* 563: 148–164.
- Williams H (2004) Birdsong and singing behavior. *Ann. N.Y. Acad. Sci.* 1016: 1–30.
- Williams H, Crane LA, Hale TK, Esposito MA, and Nottebohm F (1992) Right-side dominance for song control in the zebra finch. *J. Neurobiol.* 23: 1006–1020.
- Williams H, Cynx J, and Nottebohm F (1989) Timbre control in zebra finch (*Taeniopygia guttata*) song syllables. *J. Comp. Psychol.* 103: 366–380.
- Williams H and McKibben JR (1992) Changes in stereotyped central motor patterns controlling vocalization are induced by peripheral nerve injury. *Behav. Neural Biol.* 57: 67–78.
- Williams H and Mehta N (1999) Changes in adult zebra finch song require a forebrain nucleus that is not necessary for song production. *J. Neurobiol.* 39: 14–28.
- Williams H and Nottebohm F (1985) Auditory responses in avian vocal motor neurons: A motor theory for song perception in birds. *Science* 229: 279–282.
- Woolley SM and Rubel EW (1997) Bengalese finches *Lonchura striata domestica* depend upon auditory feedback for the maintenance of adult song. *J. Neurosci.* 17: 6380–6390.
- Yazaki-Sugiyama Y and Mooney R (2004) Sequential learning from multiple tutors and serial retuning of auditory neurons in a brain area important to birdsong learning. *J. Neurophysiol.* 92: 2771–2788.
- Yu AC and Margoliash D (1996) Temporal hierarchical control of singing in birds. *Science* 273: 1871–1875.
- Zollinger SA and Suthers RA (2004) Motor mechanisms of a vocal mimic: Implications for birdsong production. *Proc. Biol. Sci.* 271: 483–491.