

Neural Control of Birdsong

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Advanced article

Article Contents

- Introduction
- Birdsong is a Diverse Behaviour That Can be Precisely Quantified
- Anatomical Organization of the Avian Song System
- Song Production and Its Neural Control
- Song Imitation Consists of an Initial Auditory Memorization Phase Followed by Sensorimotor Learning
- Sleep and Its Role in Song Learning
- Neural Representation of the Song Auditory Template
- Anterior Forebrain Pathway as a Specialized Circuit for Sensorimotor Learning of Song
- Birdsong Research in the Genomic Age

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Birdsong is a learned behaviour that displays a remarkable level of acoustic and temporal complexity. It is controlled by a well-defined neural circuit, known as the song system, which receives highly processed auditory information from specialized higher-order auditory areas. Over the past decade, sophisticated new song analysis tools coupled with the ability to record from identified neurons in adult and juvenile singing birds have revealed many fundamental insights into the neural mechanisms that underlie vocal production, storage of auditory memories and sensorimotor learning. Some of these include an understanding of how sleep drives song acquisition and how circuits homologous to the mammalian basal ganglia generate the motor variability that enables sensorimotor learning. The tractable nature of this system coupled with its shared similarities with human speech make birdsong a unique model for understanding the neural bases of vocal production and learning.

Introduction

Songbirds are endowed with a remarkable capacity for learning and producing songs that have a high degree of

acoustic and temporal complexity. These vocalizations are under the control of a specialized neural circuit, known as the song system, which is dedicated to the learning and production of songs and calls. This circuit consists of a well-characterized network of brain structures that can be manipulated and studied in a highly precise manner. Accessibility to this circuit and the ability to study song behaviour in a highly quantitative manner have transformed birdsong into one of the most exciting areas for investigating the neural bases of complex learned behaviours. The growth and popularity of this field is exemplified by the recent publication of several books summarizing many of the latest findings (Catchpole and Slater, 2008; Marler and Slabbekoorn, 2004; Zeigler and Marler, 2008). **See also:** [Neuroethology](#)

Many fundamental neurobiological breakthroughs have been made in this system. These include the discovery of adult neurogenesis (Nottebohm, 2008) and the role steroid hormones play in the development of sexually dimorphic brains (Schlinger *et al.*, 2001). Work in this system has also provided important insights into the neural codes that underlie motor production, the auditory representation of communication signals and storage of auditory memories. This article provides a review of some of the main features of the behaviour, its underlying neural control and highlights several of the most exciting recent findings. **See also:** [Bird Song: Steroid Hormones and Plasticity](#); [Motor Output from the Brain and Spinal Cord](#)

Birdsong is a Diverse Behaviour That Can be Precisely Quantified

Songbirds belong to the order *passeriform* and are distinguished in part by the complex musculature of their vocal organ (the syrinx). With over 5000 species (out of a

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total of approximately 10 000 bird species), songbirds are one of the most diverse terrestrial orders. The diversity of song types is therefore enormous and offers a unique opportunity for comparative and evolutionary studies. Within this order, approximately 95% of the species (known as oscines) share the characteristic that much of their song is learned. The remaining species (known as suboscines) produce songs that appear to be innately specified. They also tend to lack the well-defined song system circuitry that is so striking in oscine birds (Kroodsmma and Konishi, 1991). **See also:** *Aves (Birds)*

Songbirds generally have two different types of vocalizations: calls and songs (Williams, 2008). Calls are typically of short duration and tend to be spectrally simple. They are produced by both males and females and serve specific functions such as to identify and keep track of individuals (contact calls) and warn conspecifics of predators (alarm calls) to name just a few. In contrast to calls, songs consist of longer sequences of vocalizations (syllables) that are often spectrally more complex than calls. These are generally produced to attract mates and defend territories and are therefore mostly produced by male birds although there exist species where both males and females sing. The size of a song repertoire and the complexity of the song vary significantly across species. Some songbirds have repertoires that consist of many dozens of songs (e.g. Starling and Nightingales), whereas others sing only a single song (e.g. zebra finch). Furthermore, within a song, some birds produce a diversity of different syllables (e.g. zebra finch and song sparrow), whereas others produce songs that consist of a single syllable that is repeated many times (e.g. chipping sparrow).

One of the great advantages of birdsong as a model system is the precision with which it can be quantified. Using spectrographic analysis it is possible to get a precise 'fingerprint' for individual song elements. Recent advances in computing power and storage have allowed sophisticated song analysis techniques to be used that quantify in real time many features of the bird's song (Glaze and Troyer, 2006; Tchernichovski *et al.*, 2000). These features include the dynamic spectral characteristics of each song syllable (Tchernichovski *et al.*, 2000) as well as the more global features such as song rhythm and tempo (Glaze and Troyer, 2006; Saar and Mitra, 2008). These measurements can be used to track song changes during development or be used to quantify the effect on song of precise perturbations to the various brain areas that control this behaviour.

Anatomical Organization of the Avian Song System

The avian song system contains specialized brain areas, known as nuclei, that are distributed throughout the brainstem and forebrain (both telencephalon and

diencephalon) and it can be divided into three major functional components (**Figure 1**). The descending motor pathway (shown in black) consists of forebrain areas HVC (used as proper name) and its target structure RA (the robust nucleus of the arcopallium) as well as the brainstem nuclei innervated by RA that themselves project respectively, directly and indirectly, to the muscles of the syrinx and the respiratory system. The second component is made up of ascending pathways (shown in green) that relay signals back to HVC. These pathways originate either from the thalamus (DMP, posterior portion of the dorsomedial thalamic nucleus) or from a cluster of brainstem nuclei (RAM, PAm and DM) that make up an interconnected vocal-respiratory network. The third major functional division of the song system is a basal ganglia-containing pathway, known as the anterior forebrain pathway (AFP, shown in red), that provides an indirect projection from HVC to RA. **See also:** *Thalamus*

Like all vertebrates, songbirds have two hemispheres and therefore have a 'song system' on each side of the brain. Because birds lack a corpus callosum, the massive fibre bundle that connects the left and right hemispheres in mammals, song-related neural activity in each hemisphere is thought to be synchronized by the strong bilateral projections that exist between the brainstem vocal-respiratory network (PAm and DM) and HVC via the intermediary of the thalamic relay nucleus UVa (nucleus uvaeformis; Schmidt *et al.*, 2004). The song system also receives highly processed auditory inputs from the auditory forebrain (shown in blue in **Figure 1**). Though not technically part of the song system, the auditory forebrain is critical for vocal learning and song maintenance because it processes auditory feedback and encodes the song memories that are required for song acquisition (see section on Song production and its neural control).

Avian brains, especially the telencephalon, are organized differently from their mammalian counterpart in that they do not contain a layered isocortex but are made up instead of discrete nuclei. It is therefore difficult to make direct comparisons between the various song control nuclei in birds and their counterparts in the mammalian brain. Nevertheless, there exist similarities at the level of function, projection pattern and embryonic development that allow some degree of comparison (Farries and Perkel, 2008). HVC and RA can be thought of as analogues of motor cortical areas specialized for vocal production and the auditory forebrain as analogous to auditory association cortex. The strongest evidence for homology between songbirds and mammals is with the anterior forebrain pathway. This specialized circuit has all of the features of the basal ganglia-thalamo-cortical loops (Farries and Perkel, 2008) that feature prominently in mammalian brains. A key component of these circuits is the basal ganglia and in songbirds, Area X serves as both the input (striatum) and the output (globus pallidus) portion of this structure. **See also:** *Avian Brains; Basal Ganglia and the Regulation of Movement; Brain Evolution and Comparative Neuroanatomy*

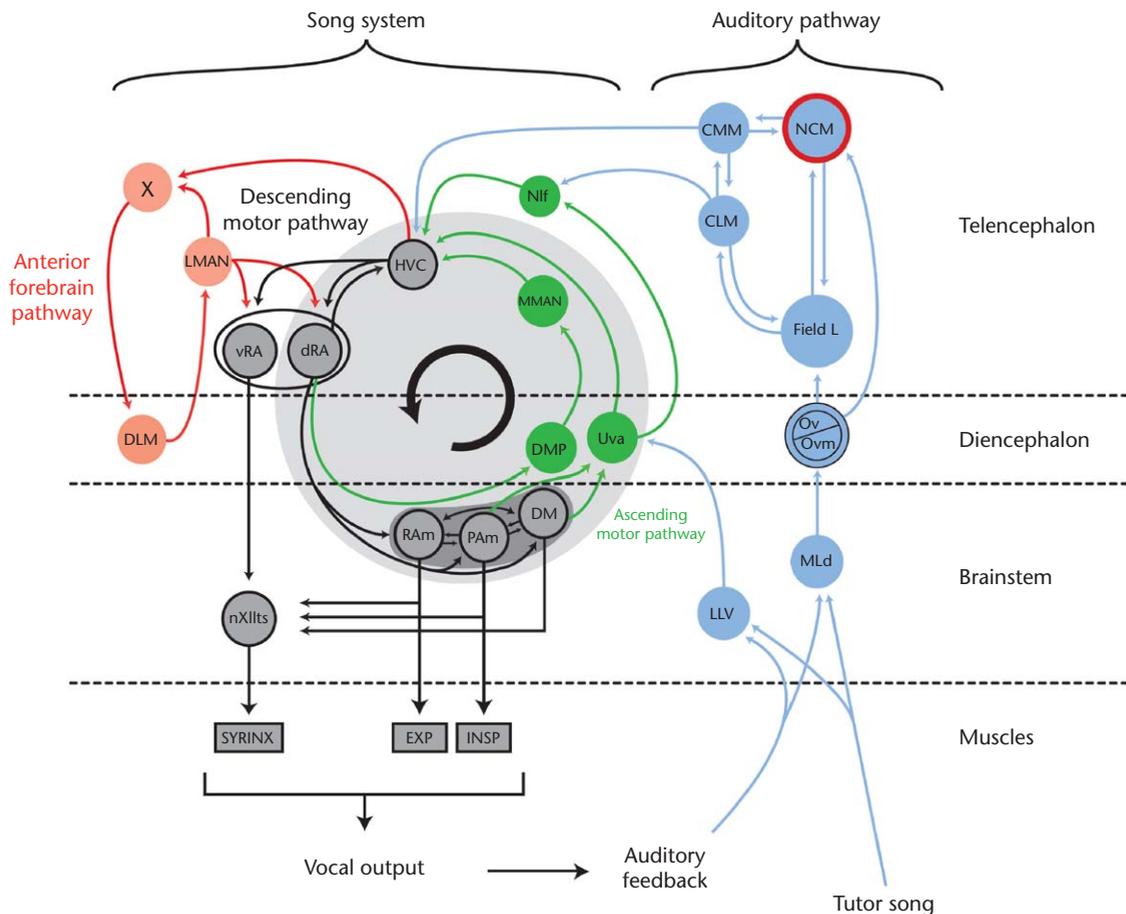


Figure 1 Schematic representation of the avian song system and its auditory inputs. The avian song system can be divided into three main divisions. The descending motor pathway (shown in black) includes telencephalic areas HVC and RA as well as brainstem nuclei that drive the muscles of the syrinx (nXllts) or the respiratory system (RAm and PAm). These later two structures form part of a vocal respiratory network that also includes DM. The second division consists of projections from the diencephalon and brainstem back to HVC (shown in green). Although not shown for simplicity, all of these projections (from PAm, DM and DMP) are bilateral in nature and therefore play a likely critical role in hemispheric coordination. The third major division of the song system consists of the anterior pathway (shown in red), which is made up of Area X, DLM and LMAN. This circuit is not necessary for song production but plays an important role in song learning and maintenance. The song system receives processed auditory information from an ascending auditory pathway (shown in blue). Area X in the auditory forebrain (highlighted with a red circle) has been suggested as the area where the song template is stored. Anatomical names: DLM, medial part of the dorsolateral thalamic nucleus; LMAN, lateral magnocellular nucleus of the anterior nidopallium; Field L, the primary auditory forebrain structure in birds; Area X, Area X of the medial striatum; Nif, nucleus interfascialis of the nidopallium; RAm, nucleus retroambiguus; PAm, nucleus paraambiguus; DM, dorsomedial nucleus of the intercollicular complex; CMM, caudal medial mesopallium; CLM, caudal lateral mesopallium; Field L, auditory forebrain areas consisting of Fields L1, L2, L2a, L2b and L3; Ov/Ovm, nucleus ovoidalis; MLd, dorsal lateral nucleus of the mesencephalon; NCM, caudal medial nidopallium and LLV, ventral nucleus of the lateral lemniscus.

Song Production and Its Neural Control

Song is produced by actively blowing air through the syrinx, a bipartite vocal organ that is divided into left and right halves that each contain an independent membranous sound source (Suthers and Zollinger, 2004). The vocal output heard from a bird's beak is therefore the sum of the sounds generated from each 'sound box'. The existence of separate sound sources often leads to individual song syllables being produced by the rapid alternation of different sounds produced in each syringeal half (Figure 2). This rapid switching is so perfectly synchronized that the acoustic

output is completely smooth across transitions. Because muscles on each half of the syrinx receive separate sets of motor commands from their respective ipsilateral motor pathways (Wild, 2008), synchronization of muscle activity in each syringeal half requires tight coordination of the motor commands generated in each hemisphere (Schmidt, 2003). This synchronization is so much the more critical given recent evidence suggesting that motor commands generated in each hemisphere seem to alternate rapidly between sides during song production (Wang *et al.*, 2008).

The motor commands for most aspects of song are currently thought to originate in HVC. This conclusion is based on lesion studies and experiments that use brief

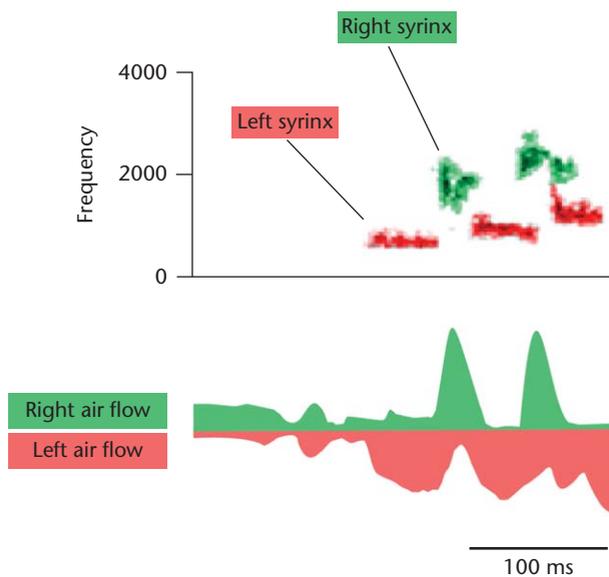


Figure 2 Songbirds can switch rapidly between sides when they sing. Many songbirds use both their left and right syrinx to produce song. In some cases, as illustrated here by the brown-headed cowbird, they can switch rapidly from producing sound in the left syrinx to produce sound in the right syrinx. In this example, a cluster of 5 short song elements is produced within a very short period of approximately 200 ms. The contribution of each syringeal side can be measured by implanting a small heated microbead thermistor in each primary bronchus. This measures the rate of airflow through each side of the syrinx and is shown at the bottom of the figure with airflow from the right side in green and from the left side in red. Note the left airflow has been flipped upside down to better compare with the right side. From these measurements, one can infer the syringeal source of each song element. As shown in the sonogram, cowbirds rapidly alternate between producing a note with the left (red) and the right (green) sides of the syrinx. (This cartoon is based on measurements recorded by Dr. Rod Suthers.) Adapted from Figure 2 in Schmidt MF (2008) *PLoS Biology* 6(10): 2089–2093.

electrical stimulation to perturb song as well as a recent study that uses cooling to perturb HVC and song activity (Long and Fee, 2008). In this study cooling HVC, but not in RA, causes a stretching of song across all song elements (including the gaps of silence between syllables) but has only minor effects on the spectral properties of song. This suggests that motor commands generated in HVC control many, although perhaps not all, aspects of song timing. Recordings in singing birds from single neurons that serve as the output of HVC, also known as HVC_{RA} neurons because they project to RA, reveal that the motor code in HVC is quite unique. Specifically, individual HVC_{RA} neurons produce only a single short (5–10 msec long) burst of three to six action potentials per song motif (Hahnloser *et al.*, 2002; **Figure 3**). Each HVC_{RA} projection neuron is therefore presumed to be associated with only a single approximately 10 ms segment of each syllable in the song. Repetitions of a syllable, as would occur during the production of multiple motifs, results in a given HVC_{RA} neuron bursting at the exact same time for each identical syllable with a temporal jitter across renditions that is less than 1 ms. Based on these findings, it has been proposed that each consecutive 10 ms time window of a syllable is

encoded by a distinct population of neurons in HVC (Fiets *et al.*, 2004). The output of each population, which is estimated to be between 100 and 200 neurons, would then drive the neurons in RA. These neurons are equally precise in their firing pattern but produce multiple bursts during any given motif. RA is organized such that its dorsal portion (dRA) sends projections to the respiratory brainstem, whereas its more ventral portion (vRA) innervates a portion of the hypoglossal nucleus which itself innervates the different muscles of the syrinx (Vicario, 1991). Interestingly, the portion of RA that projects to the respiratory brainstem also sends a projection back to HVC (Roberts *et al.*, 2008). A schematic of the sparse code model for song production is shown in **Figure 4**.

Song Imitation Consists of an Initial Auditory Memorization Phase Followed by Sensorimotor Learning

Songbirds have a remarkable capacity for learning songs that are acoustically and temporally complex. Most birds copy their song as juveniles from either their father or other conspecific males although it is possible to have them learn from tape recordings under certain laboratory settings (Catchpole and Slater, 2008). Several species, such as zebra finches, are referred to as ‘closed-ended’ learners because they retain the song they learn as juveniles for the remainder of their lives. By contrast, ‘open-ended’ learners such as the canary, retain the ability to modify their existing song and learn new songs as adults. Song learning can be divided into two general phases: an initial ‘sensory’ phase when birds have to memorize a song template, followed by a ‘sensorimotor’ phase when birds must match their vocal output to the memorized song template. For ‘closed-ended’ learners, juveniles must be exposed to a song tutor during a relatively short critical period in their life. If they are raised in the absence of a song model, or if the song model is presented after this critical period, birds develop an ‘isolate’ song, which bears only little resemblance to the normal song of their conspecifics. Interestingly, species-specific song aspects such as tempo often remain in these birds implying that certain aspects of song timing might be encoded innately.

Aside from the obvious necessity of hearing and memorizing the tutor song, birds also need to hear themselves sing during the ‘sensorimotor’ phase to develop a normal song. Preventing auditory feedback, even if this occurs after exposure to the tutor song, results in the production of a highly abnormal song. In fact, songs produced by deafened birds are much more abnormal than ‘isolate’ songs in that syllables completely lack the acoustic features of normal syllables and never achieve the overall temporal structure that is observed even in ‘isolate’ songs. Interestingly, auditory feedback is still necessary even after birds have crystallized their songs because deafening of adult birds causes song to deteriorate after several weeks. The

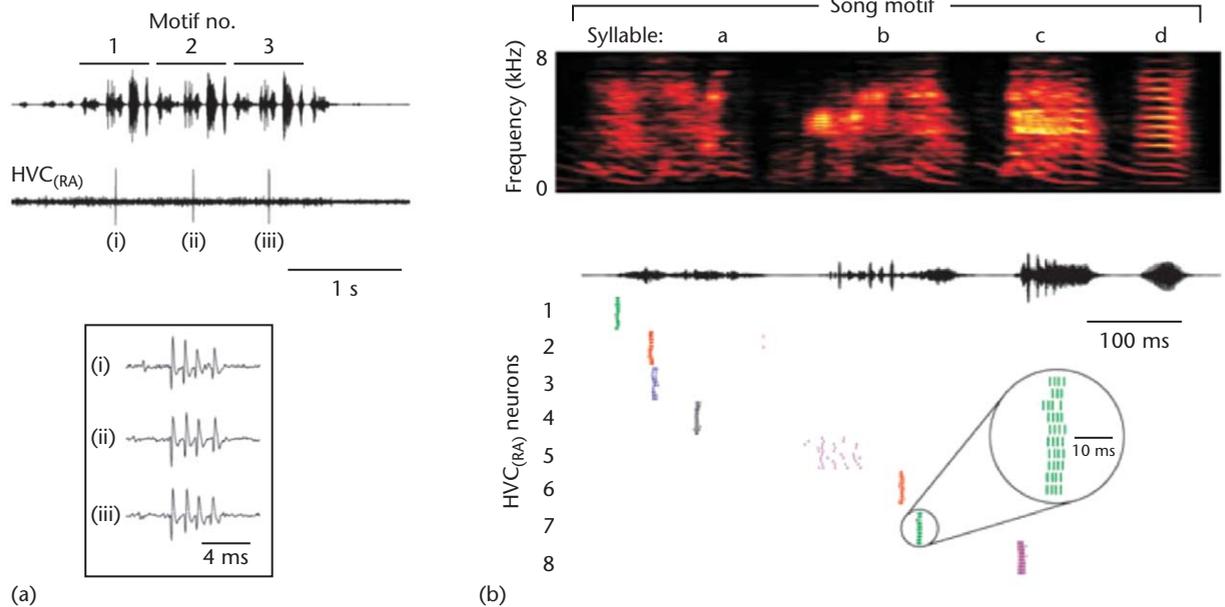


Figure 3 Sparse neural representation in HVC during singing. (a) Single-unit recording in HVC of an RA-projection neuron (HVC_{RA}) during the production of three sequential song motifs (top trace) reveals that this neuron only produces a single burst of action potentials (i, ii and iii) at precisely the same time in each song motif. The boxed inset shows an expanded view of each burst. (b) A spike raster plot is shown for eight different HVC_{RA} neurons recorded in the same bird where each row of tick mark represents action potentials generated during one rendition of the song. Each recorded neuron is represented by a separate colour. This graph illustrates the precision with which HVC_{RA} neurons burst at exactly the same time period in each motif. It also shows how different neurons fire preferentially at different time periods in the motif. Reproduced from Hahnloser *et al.* (2002), Figure 2. With permission from Macmillan Publisher Ltd.

dependency of auditory feedback on song maintenance appears to be age-dependent because birds with recently crystallized songs are much more rapidly affected by deafening than older more mature birds (Lombardino and Nottebohm, 2000).

In zebra finches, as in many songbird species, sensorimotor learning is divided into three stages: subsong, plastic song and crystallized song. Subsong likely develops out of the bird's nestling begging call and consists of noisy 'babbling' that is produced with no identifiable structure. Following subsong, juvenile birds transition to a *plastic song* where they start producing elements that resemble those in the tutor song. These songs are arranged in a sequential, but still variable, manner. Once song syllables start being produced in a stereotyped sequential manner, song is said to be crystallized (approximately 100 days of age in zebra finches). Contrary to what might be expected, normally raised and tutored juvenile songbirds do not use a single strategy to learn their song (Liu *et al.*, 2004). Even among siblings from a same clutch, some birds will choose a 'serial repetition strategy' while others will opt for a 'motif strategy'. Birds that choose the serial repetition strategy produce a single precursor syllable that they repeat in long sequences. With time, they modify the acoustic features and duration of each of these syllable precursors to eventually produce a song that matches the template. Birds that use the 'motif strategy', however, start by producing a global imitation of the father's song with each element already in the right place in the motif but produced in a very noisy and imprecise way. With time birds refine the

acoustic properties of each element without any major modifications to the sequence (Tchernichovski *et al.*, 2001).

Sleep and Its Role in Song Learning

Juvenile birds start to imitate aspects of the tutor song almost immediately after they are exposed to the tutor song. Interestingly, birds exhibit a specific daily pattern to their singing behaviour following exposure to the tutor song. This pattern lasts the entire duration of the song learning process and consists of birds singing songs in the morning that are less complex when compared to the songs they produce in the afternoon (Deregnacourt *et al.*, 2005). More importantly, the songs they produce in the morning are always less complex than the songs they produced the previous afternoon. This difference in song quality is directly linked to sleep-specific processes and appears to be necessary for the vocal imitation process to occur because the magnitude of the daily variation in song quality is positively correlated with the final quality of the copied song. In other words, birds that exhibit the greatest change in song structure each morning are the birds that ultimately achieve the best song copying. **See also:** [Sleep](#)

Exposure to the tutor song will cause birds to increase their singing rate but the resulting circadian pattern only emerges the day after exposure. This delay in singing behaviour to the following day implies that physiological processes that are expressed during sleep are involved in these changes (Shank and Margoliash, 2008). Insight into

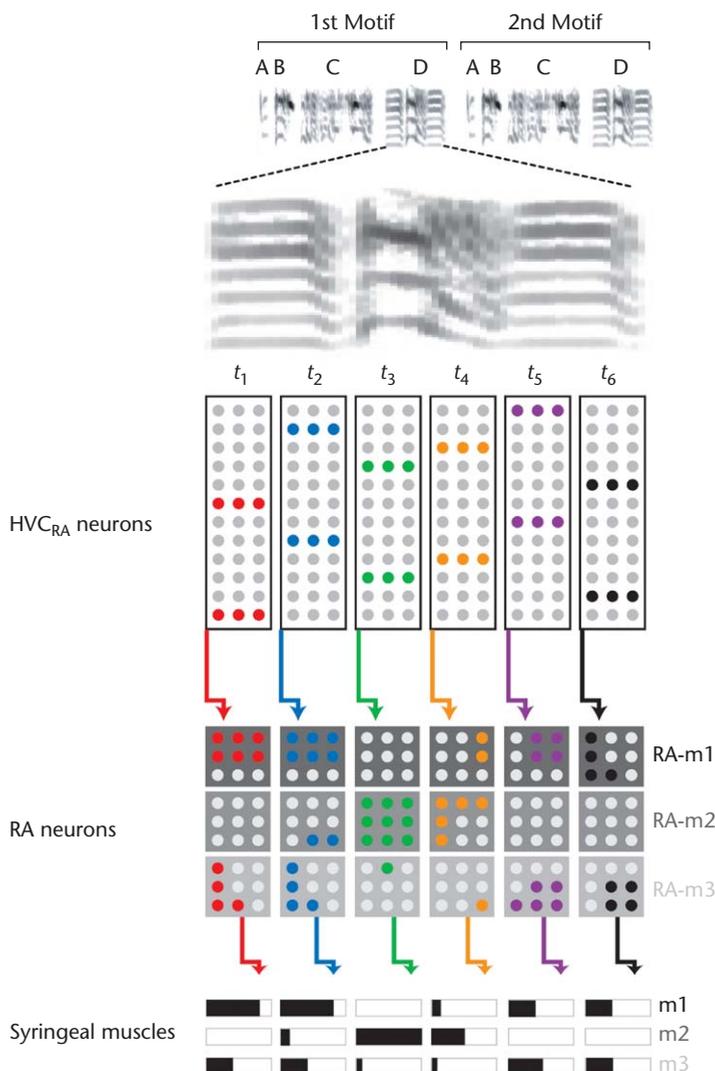


Figure 4 Conceptual representation of the ‘sparse code’ model for song production. During the production of song in the zebra finch (top panel: ‘SONG’), single HVC_{RA} neurons fire only a single burst during the entire duration of the motif, which occurs at exactly the same acoustic transition from one motif to the next. It has been hypothesized that approximately 100–200 neurons will be active simultaneously (i.e. produce a single burst) during each 10 ms time window (*t*). The second panel (‘HVC_{RA} neurons’) shows a schematic representation of this concept by dividing syllable ‘d’ into discrete time windows (*t*₁, *t*₂, *t*₃, *t*₄, ...) where different subpopulation of HVC_{RA} neurons (red cells during *t*₁, blue cells during *t*₂, etc.) are active during each time window. Each of these subpopulations of HVC_{RA} neurons (e.g. blue cells in window *t*₂) is thought to activate a discrete population of neurons in RA (shown in the third panel ‘RA neurons’). To represent the known myotopic map, RA is divided into three sections (RA-m1, RA-m2 and RA-m3). For simplicity, the nXIIts layer has been omitted and only three of the six muscle groups are represented (lowest panel ‘syringeal muscles’). Activation of a specific subset of neurons in RA recruits various muscle groups and results in a distinct acoustic output for that specific window in time. In the case of window *t*₁, for example, activation of the red cell population in HVC leads to activation of a subset of neurons in RA which, in this example, activate muscle 1, a little bit of muscle 3 and not muscle 2.

brain mechanisms can be obtained by comparing the spontaneous activity of RA neurons recorded on nights before and following exposure to the tutor song. Before tutor song exposure, RA neurons show relatively little high-frequency activity but this activity increases dramatically on the first night after exposure. These changes in RA bursting activity are observed only if birds can hear themselves sing suggesting that auditory feedback shapes the changes in network properties that occur during sleep (Shank and Margoliash, 2008). Because changes in RA activity are observed on the night after tutor song exposure,

but before changes in singing behaviour are detected the following morning, it is hypothesized that a memory trace of the tutor song alters the vocal-motor networks during sleep to allow for the change in singing behaviour.

Neural Representation of the Song Auditory Template

Birds exposed to song from a tutor end up storing that song into memory so that it can be accessed and used as

a template to guide the vocal imitation process. Early work in search of the site for such memory formation focused on the song system itself. This was fuelled by findings that lesions within the anterior forebrain pathway could prevent song learning (Bottjer *et al.*, 1984) and that auditory responses within this pathway were shaped during the vocal learning process (Doupe and Solis, 1997). Recent experiments suggest that the auditory template of the tutor song is likely stored in higher-order auditory forebrain areas rather than in the song control system.

The avian auditory pathway is organized in a similar way to its mammalian counterpart (Theunissen *et al.*, 2008). Auditory information is first processed in the brainstem before it is relayed to the forebrain via the thalamic nucleus ovoidalis (nOv), the avian equivalent of the medial geniculate nucleus. Auditory information is then transmitted to Field L (analogous to primary auditory cortex) before it is sent to a highly interconnected network of auditory forebrain areas. From these areas, auditory information eventually reaches the song system via Nif (interfacial nucleus of the nidopallium), which together with the forebrain auditory area CMM (caudal medial mesopallium) provide the major auditory input into HVC and the rest of the song system (see **Figure 1**; Bauer *et al.*, 2008; Cardin *et al.*, 2005). Neurons in many areas of the auditory system of adult songbirds, from the midbrain inferior colliculus (MLd) to the higher order auditory forebrain areas, are particularly sensitive to the spectral and temporal structure found in conspecific songs and calls. These findings suggest that the auditory system in songbirds is highly specialized for processing acoustic signals that relate specifically to song. **See also:** [Auditory Processing](#); [Brainstem](#)

Early work investigating auditory properties in songbirds focused on the extraordinary auditory selectivity in HVC, RA and LMAN (lateral magnocellular nucleus of the anterior nidopallium), a forebrain area that serves as the output nucleus of the anterior forebrain pathway onto RA. Neurons in each of these structures respond vigorously to the bird's own song (BOS) but show little to no responsiveness to conspecific song or simpler stimuli like white noise or tones (Margoliash, 1986). This selectivity does not result from increasing selectivity for BOS throughout the ascending auditory pathway but arises rather abruptly at the level of Nif and HVC (Coleman and Mooney, 2004). Interestingly, this selectivity is observed primarily in sleeping or sedated birds and is much less apparent in awake birds suggesting that auditory responses in the song system is strongly modulated by the animal's behavioural state (Cardin and Schmidt, 2003). Because neural selectivity in these song system areas changes as the bird learns and modifies its song, it was initially believed that the song system might be the site where the song template is stored. Subsequent studies have failed to find strong evidence that the song template is stored in the song system and it is therefore now believed that this system is more intimately linked to sensorimotor learning rather than storage of auditory memories.

The two most prominent candidates structures for storing auditory memories are the forebrain auditory areas

NCM (caudal medial nidopallium) and CMM (Bolhuis and Gahr, 2006). Neurons in both of these areas do not show selectivity for the BOS but instead respond most strongly to stimuli, such as conspecific song, that have behavioural significance to the bird. Both of these areas also show increased responsiveness (measured either electrophysiologically or by the expression of immediate early genes) to songs that birds have been exposed to previously. In NCM, responsiveness is expressed in a somewhat unusual way. Neurons in this structure show their specificity by the rate with which they habituate to the repeated presentation of auditory stimuli. Specifically, NCM neurons habituate more rapidly to the repeated presentation of familiar songs than they do to novel songs suggesting this structure plays a role in discriminating familiar songs from novel ones (Mello *et al.*, 1995).

The discrimination between familiar and novel songs in NCM appears to extend to the tutor song. NCM responses habituate more rapidly to the tutor song than to novel songs and the rate of habituation is directly proportional to how well the bird copies the song template (Phan *et al.*, 2006). Additional evidence comes from experiments showing that immediate early gene expression levels (a molecular proxy for neural activation) in NCM are directly proportional to the strength of song learning (Bolhuis *et al.*, 2000). The most convincing evidence to date that NCM might store song auditory memories involves the use of pharmacological blockade in NCM in a paradigm where tutor song presentation can be dissociated in time from vocal rehearsal (London and Clayton, 2008). Blocking activity in NCM selectively during presentation of the tutor song prevents birds from storing the song template in NCM and causes them to develop a highly abnormal song that resembles 'isolate' song.

Anterior Forebrain Pathway as a Specialized Circuit for Sensorimotor Learning of Song

Exposure to the tutor song initiates a song imitation process that drives birds to try and match their vocalizations to the memorized song template. Auditory feedback of each song attempt is therefore used as a corrective signal to minimize the error between the song the bird produces and the memorized tutor song. This corrective signal is then used to modify the neural circuits that drive vocal production so that ensuing song attempts more closely resemble the song template. The use of sensory feedback to modify motor output is known as sensorimotor learning and it lies at the heart of the song learning process. A highly effective approach to investigate the brain areas involved in sensorimotor learning is to use combinations of anatomical and pharmacological techniques to perturb brain areas in adults and juveniles at different periods of song development.

In adult birds, bilateral lesions of RA completely abolish song production and result in zebra finches that only

produce short calls that lack the acoustic features associated with vocal learning (Simpson and Vicario, 1990). These results imply that RA and its downstream targets are necessary for the production of all learned vocalizations. Bilateral lesions of HVC also abolish the production of normal adult song but in contrast to RA, where birds only produce short calls, HVC lesioned birds produce vocalizations that are reminiscent, and statistically identical, to juvenile subsong (Aronov *et al.*, 2008). In the absence of HVC, vocal production therefore appears to be driven by

inputs from LMAN onto RA. This hypothesis is confirmed by the complete disappearance of these subsong-like vocalizations following bilateral LMAN lesions.

The influence that LMAN exerts on RA is believed to be essential for sensorimotor learning in juvenile birds. Bilateral lesions of LMAN in otherwise intact young birds result in the abrupt stabilization of the bird's immature and variable plastic song (Scharff and Nottebohm, 1991). In fact, songs that would have otherwise developed into accurate copies of the tutor song remain instead

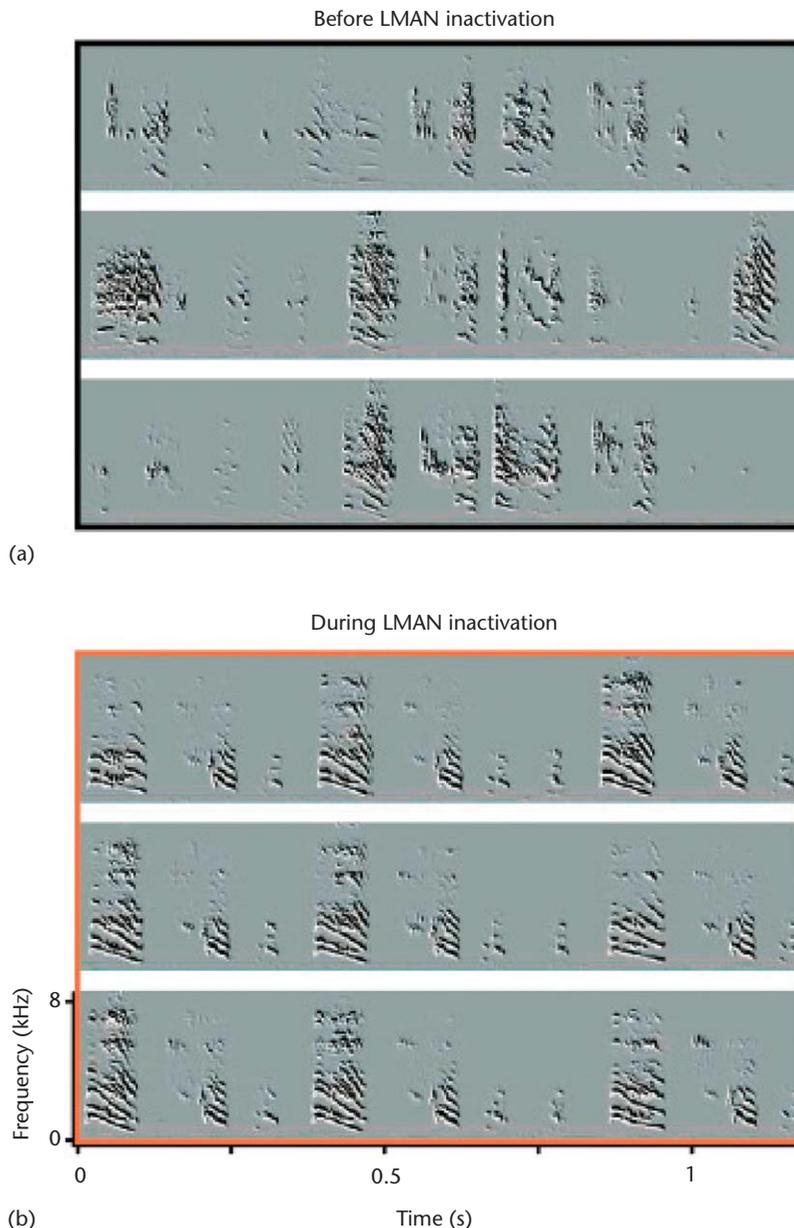


Figure 5 Effect of pharmacological silencing LMAN on plastic song. (a) Sonographic representation of three different song renditions of a juvenile zebra finch (57 days posthatch) show large variability in the sequence and acoustic structure of song syllables. (b) TTX was then injected into LMAN and song output was recorded a short duration thereafter. Inactivation of LMAN with TTX produces an immediate reduction of sequence and acoustic variability, revealing a highly stereotyped song produced by the descending motor pathway. The song segments shown in (a) and (b) are from consecutive song bouts, immediately before and 1 h after TTX injection. Modified from Figure 1 in Olveczky *et al.* *PLoS Biology* 3(5): e153.

acoustically frozen in their immature state. Interestingly, reversible injection in juvenile birds of agents that suppress activity in LMAN such as TTX or muscimol (Olviczky *et al.*, 2005) not only freeze the song in its current state but also remove acoustic variability that seems to be overlaid on the immature song (Figure 5). LMAN therefore appears to 'inject' motor variability via its glutamatergic projections to RA and in so doing is able to cause a functional remodeling of the circuits in RA that lead to a direct change in behavioural output. This apparent 'explore-exploit' strategy used by songbirds also appears to be used during sensorimotor learning by basal ganglia circuits in mammals.

The generation of motor variability thought to lie at the core of the motor exploratory process during song learning is also essential for vocal plasticity in adult songbirds (Brainard and Doupe, 2002). In adults, peripheral manipulations such as deafening or syringeal nerve cuts cause the normally stereotyped song of zebra finches to change within 4–6 weeks. These changes include the insertion of new song elements, the acoustic modification of existing elements and, in some cases, the deletion of existing elements. Similar song deterioration can be achieved by placing small electrolytic lesions in HVC. Interestingly, lesions of LMAN made before these peripheral as well as central manipulations completely prevent these changes suggesting that the AFP is causative in the generation of these vocal changes (Brainard and Doupe, 2000; Thompson *et al.*, 2007; Williams and Mehta, 1999).

Birdsong Research in the Genomic Age

Recent recognition by the National Institutes of Health (NIH) that songbirds offer unique opportunities for understanding the basic biology of vocal production and learning prompted them to select the zebra finch for whole-genome sequencing (see <http://www.ncbi.nlm.nih.gov/genome/guide/finch/>). Availability of the zebra finch genome will enable a whole new generation of studies that are able to target the role of specific genes in various aspects of song behaviour and evolution (Clayton and Arnold, 2008). Several recent experiments have started using these new approaches to ask questions about the role in song development of genes that have strong homologies with human genes implicated in certain language disorders. One such candidate is the *FOXP2* (forkhead box P2) gene, a transcription factor whose mutation is thought to underlie developmental verbal dyspraxia in humans. *FOXP2* in both humans and songbirds shows strong expression patterns in the basal ganglia, thalamus and cerebellum. Because *FOXP2* expression patterns peak transiently in Area X at the height of song learning (Teramitsu *et al.*, 2004), it has been possible to test whether reducing *FOXP2* levels would interfere with song learning in a way consistent with the proposed role for the AFP in song learning. Using viral-mediated ribonucleic acid (RNA) interference methods, knockdown of *FOXP2* levels in Area X disrupts normal song learning (Haesler *et al.*, 2007). The use of these

types of methods to dissect the circuits involved in song production and learning is likely only the beginning of a new generation of experimental manipulations. These will likely provide a rich characterization, from gene to circuit to behaviour, of the neural mechanisms that underlie complex learned vocal behaviours and how they might relate to human disease.

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Further Reading

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