



Available online at [www.sciencedirect.com](http://www.sciencedirect.com)



Behavioural Brain Research xxx (2006) xxx–xxx

**BEHAVIOURAL  
BRAIN  
RESEARCH**

[www.elsevier.com/locate/abbr](http://www.elsevier.com/locate/abbr)

Review

# On the role of the reticular formation in vocal pattern generation

Uwe Jürgens\*, Steffen R. Hage

*Department of Neurobiology, German Primate Center, Kellnerweg 4, 37077 Göttingen, Germany*

Received 25 August 2006; received in revised form 15 November 2006; accepted 16 November 2006

## Abstract

This review is an attempt to localize the brain region responsible for pattern generation of species-specific vocalizations. A catalogue is set up, listing the criteria considered to be essential for a vocal pattern generator. According to this catalogue, a vocal pattern generator should show vocalization-correlated activity, starting before vocal onset and reflecting specific acoustic features of the vocalization. Artificial activation by electrical or glutamatergic stimulation should produce artificially sounding vocalization. Lesioning is expected to have an inhibitory or deteriorating effect on vocalization. Anatomically, a vocal pattern generator can be assumed to have direct or, at least, oligosynaptic connections with all the motoneuron pools involved in phonation. A survey of the literature reveals that the only area meeting all these criteria is a region, reaching from the parvocellular pontine reticular formation just above the superior olive through the lateral reticular formation around the facial nucleus and nucleus ambiguus down to the caudalmost medulla, including the dorsal and ventral reticular nuclei and nucleus retroambiguus. It is proposed that vocal pattern generation takes place within this whole region.

© 2006 Elsevier B.V. All rights reserved.

*Keywords:* Vocalization; Phonation; Pattern generation; Reticular formation; Nucleus retroambiguus; Periaqueductal gray; Squirrel monkey

## Contents

1. Introduction .....	00
2. Criteria to identify a vocal pattern generator .....	00
3. Applying the criteria to the currently available data .....	00
3.1. Single-unit recording data .....	00
3.2. Electrical stimulation data .....	00
3.3. Lesion data .....	00
3.4. Anatomical data .....	00
4. Conclusion .....	00
References .....	00

*Abbreviations:* Ab, nucleus ambiguus; AS, aquaeductus Sylvii; BC, brachium conjunctivum; BP, brachium pontis; Cb, cerebellum; CN, nucleus cochlearis; Cn, nucleus cuneatus; CRf, corpus restiforme; DG, nucleus dorsalis tegmenti (Gudden); dLL, nucleus dorsalis lemnisci lateralis; DLM, decussatio lemnisci medialis; DPy, decussatio pyramidum; DR, nucleus dorsalis raphae; DRt, nucleus reticularis dorsalis; DV, nucleus dorsalis n. vagi; FRM, formatio reticularis myelencephali; FRMg, formatio reticularis gigantocellularis; FRMp, formatio reticularis parvocellularis; FRP, formatio reticularis pontis; GPo, griseum pontis; IC, colliculus inferior; LC, locus coeruleus; LL, lemniscus lateralis; LM, lemniscus medialis; MV, nucleus motorius n. trigemini; NSV, nucleus spinalis n. trigemini; NTS, nucleus tractus solitarii; OI, oliva inferior; PAG, griseum periaqueductale; PbL, nucleus parabrachialis lateralis; PbM, nucleus parabrachialis medialis; Pp, nucleus praepositus; PV, nucleus principalis n. trigemini; Py, tractus pyramidalis; RAb, nucleus retroambiguus; RL, nucleus reticularis lateralis; SC, colliculus superior; SN, substantia nigra; SOC, oliva superior complex; Th, thalamus; TSc, tractus spino-cerebellaris; TTS, tractus tectospinalis; VesI, nucleus vestibularis inferior; VesL, nucleus vestibularis lateralis; VesM, nucleus vestibularis medialis; VR, nucleus ventralis raphae; VRt, nucleus reticularis ventralis; VI, nucleus abducens; VII, nucleus facialis; XII, nucleus hypoglossus

\* Corresponding author. Tel.: +49 551 3851250; fax: +49 551 3851302.  
E-mail address: [ujuerge@gwdg.de](mailto:ujuerge@gwdg.de) (U. Jürgens).

## 1. Introduction

Vocal behavior is found essentially in two forms. One is characterized by genetically preprogrammed vocal patterns. An example is pain crying. An infant does not need to hear and exercise crying in order to be able to produce it. A heavy blow against the body will elicit crying without any prior experience. Studies in deaf-born infants reveal that, in addition to crying, a number of other non-verbal emotional vocal utterances also are genetically determined [45]. Furthermore, almost all non-human mammalian vocalizations belong to this type [19]. The other type of vocal behavior is characterized by vocal patterns learned by imitation or invention. Human speech is one example; human song as well as the songs of birds and whales are others. Experimental brain lesioning studies in animals and neurological investigations in brain-lesioned patients have made clear that there are a number of brain areas necessary for the production of learned vocal patterns, but dispensable for the production of innate vocal patterns. Such areas are, for instance, the primary motor cortex, putamen, ventrolateral thalamus and cerebellum (for review, see [24]). In fact, early brain transection experiments in cats by Bazett and Penfield [2] have shown that the whole forebrain and rostral half of the midbrain can be removed without interfering with the ability to produce species-specific vocalizations. Also tests in human anencephalic infants, more specifically, infants born without forebrain, rostral midbrain and cerebellum, have shown that such infants still are able to cry when exposed to painful stimuli [40]. These observations make clear that the neuronal network responsible for the production of species-specific vocalizations is located in the brainstem below the rostral midbrain level. In the following, an attempt will be made to further specify the location of that network.

One of the first brain structures in the brainstem assumed to play a specific role in the production of species-specific vocalization was the periaqueductal gray of the midbrain (PAG). Lesioning studies in rats, cats, dogs, squirrel monkeys and human patients have reported mutism after destruction of this region (for review, see [22]). Electrical stimulation of the PAG has yielded species-specific vocalization in a number of species [22]. Apart from electrical stimulation, also pharmacological stimulation, that is, injection of glutamate agonists and GABA antagonists into the PAG, have yielded vocalization [1,11,33], suggesting that the PAG is not just a through-station of a descending vocalization pathway, but represents a relay station in which processing of vocal information takes place. Finally, single-unit recording studies have shown that the PAG contains neurons the activity of which is correlated with vocalization and, in some cases, even with the activity of single laryngeal and respiratory muscles [30]. From these observations, a number of authors concluded that the vocal pattern generator for species-specific vocalization is located in the PAG [10,21,30].

In a more recent study in the squirrel monkey, it was found that pharmacological inactivation of the PAG, leaving the animal unable to vocalize to external stimuli and electrical stimulation of the forebrain, did not prevent the production of species-specific vocalizations by electrical stimulation of the lower brainstem [48]. This observation was confirmed for the bat by

Siebert and Schuller [49]. Both observations speak against the PAG as the site of vocal pattern generation.

## 2. Criteria to identify a vocal pattern generator

In the quest of localizing the vocal pattern generator, the first step has to be to specify experimentally testable characteristics by which a vocal pattern generator can be identified. In the following, a catalogue of such characteristics is given:

- (1) A vocal pattern generator should contain neurons with vocalization-correlated activity. The activity should reflect specific acoustic features of the vocalization and should start prior to vocal onset.
- (2) Electrical stimulation of a vocal pattern generator should produce vocalization. Due to the artificial activity pattern forced upon the neurons by electrical stimulation, the elicited vocalization should have an artificial character.
- (3) Elicitation of vocalization should be possible not only by electrical, but also by pharmacological (glutamate agonist or GABA antagonist) stimulation.
- (4) Lesions or pharmacological inactivations of the vocal pattern generator, or of parts of it, should have an inhibitory or deteriorating effect on vocalization. Sites at which lesions or pharmacological inactivations do not affect the acoustic structure of vocalization are not part of the vocal pattern generator.
- (5) Anatomically, the vocal pattern generator should have mono- or oligosynaptic connections to all motoneuron pools involved in phonation. In other words, the vocal pattern generator should have a rather direct control on the phonatory motoneurons.

## 3. Applying the criteria to the currently available data

### 3.1. Single-unit recording data

Vocalization-correlated single-unit activity has been reported for the following brainstem structures: PAG, lateral mesencephalic tegmentum, deep layers of the superior colliculus, pericentral nucleus of the inferior colliculus, nucleus cuneiformis, lateral parabrachial nucleus, paralemniscal area, parvocellular pontine and medullary reticular formation, giganto- and paragigantocellular reticular formation, dorsal and ventral medullary reticular nuclei, nucleus retroambiguus, nucleus ambiguus, facial nucleus, trigeminal motor nucleus, spinal trigeminal nucleus, solitary tract nucleus, medial and inferior vestibular nuclei [12,18,30,34,39,43]. A comparison of activity onset times between phonatory motoneurons and any of the other structures mentioned was made only for the supraolivary parvocellular reticular formation [18]. In this case, with the exception of only one neuron, for each phonatory motoneuron a reticular neuron could be found, firing before the motoneuron. In other words, in the phase of vocalization initiation, the activity of the supraolivary reticular formation precedes that of the phonatory motoneurons—a *conditio sine qua non* for a vocal pattern generator. In the other structures with vocalization-correlated activity,

comparisons were made only between the onset time of neuronal activity and that of vocal sound. In all these structures, neurons with pre-vocalization activity were found.

Another feature considered to be essential for a vocal pattern generator is its capacity to code the acoustic structure of vocalization. Neurons showing a correlation in their activity with specific acoustic parameters, such as fundamental frequency, amplitude or duration, have been found in the lateral pontine and medullary reticular formation, dorsal and ventral reticular nuclei of the caudal medulla, nucleus retroambiguus, nucleus ambiguus, facial nucleus, spinal trigeminal nucleus and solitary tract nucleus [18,34]. Fig. 1 shows the anatomical distribution of neurons in the squirrel monkey, changing their discharge rate in relation to changes in fundamental frequency and/or amplitude.

There is some controversy in the literature about the pattern-coding capacity of the PAG. According to Larson [30], 4% of the PAG neurons with vocalization-related activity changes show a correlation with the maximum fundamental frequency; 4% show a correlation with vocalization duration and 24% show a correlation with loudness. Furthermore, spike-triggered averaging of electromyographic activity revealed a close relationship between PAG single-unit activity and activity of single laryngeal and respiratory muscles. These observations point to a quite direct control of the phonatory muscles by the PAG. On the other hand, Düsterhöft et al. [12] were unable to find neurons in the PAG, changing their discharge rate in relation to frequency or amplitude modulations within a call. The latter study was carried out in squirrel monkeys which, apart from calls with a more or less constant frequency course, also have calls with extensive frequency modulations. The Larson study investigated macaque “*coo*” calls which lack marked frequency and amplitude modulations. As a consequence, correlations with single-unit activity were calculated in the Larson study only for the call as a whole, not for the moment-to-moment change in acoustic structure. In the Düsterhöft et al. study, it was found that many of the PAG neurons show a high call-type specificity. There are neurons firing during rhythmically frequency-modulated “*twitter*” calls, but not during constant-frequency “*peep*” calls, despite the fact that the average fundamental frequency is about the same in both cases. There are neurons firing to high-pitched constant frequency calls (“*peep*”), but not to low-pitched constant frequency calls (“*caw*”), and vice versa. There are neurons firing to a combination of two calls (“*growlchuck*”), but not to each of the calls alone. These observations suggest that the PAG codes vocalization in a more holistic manner, determining the call type and global intensity rather than the fine-grained frequency/amplitude/time structure.

### 3.2. Electrical stimulation data

Systematic exploration of the brainstem of the cat, rhesus monkey and squirrel monkey with electrical stimulation revealed an extensive system of vocalization-eliciting sites, reaching from the PAG through the lateral mesencephalic and pontine tegmentum into the caudalmost dorsal and ventral medullary reticular formation (Fig. 2; [26,35]). As electrical stimulation activates synaptic regions as well as by-passing fibers, its localizing power

is limited. In other words, electrical brain stimulation can help to delimit the neural vocalization network as a whole; it cannot identify, however, the modal points of the system, that is, the sites at which processing of vocalization takes place. A more specific approach than electrical stimulation is pharmacological stimulation with glutamate agonists or GABA antagonists. In this case, only synaptic regions, not by-passing fibers, are activated. In the squirrel monkey, a systematic exploration for vocalization-eliciting sites was carried out with glutamate [28]. The study showed that the glutamate-effective vocalization sites follow the course of the electrical vocalization sites, that is, glutamate-induced vocalization can be obtained from the PAG, lateral mesencephalic and pontine tegmentum as well as the dorsal and ventral reticular nuclei of the medulla. The only difference between electrical and pharmacological stimulation is that only a small fraction of the electrically effective sites yield vocalization with glutamate, while all glutamate-positive sites yield vocalization with electrical stimulation (Fig. 2). With respect to the type of vocalization elicitable, it turned out that vocalizations elicitable from the PAG, lateral mesencephalic and uppermost pontine tegmentum have a normal species-specific structure, whereas vocalizations elicitable from the caudal ventrolateral pons and medullary reticular formation have an abnormal acoustic structure, even when evoked with threshold currents. As mentioned above, the artificial character of the vocalizations elicited from the caudal pons and medulla indicates that in these regions the stimulant interferes directly with the vocal patterning process. As can be seen from Fig. 2, the critical sites are localized in the pontine parvocellular reticular formation just above the superior olive, in the medullary reticular formation bordering the facial nucleus and nucleus ambiguus and in the dorsal and ventral reticular nuclei of the medulla at the level of the nucleus retroambiguus.

### 3.3. Lesion data

Only few brainstem structures have been tested with respect to their lesion effects on spontaneous vocalization. These are the PAG, lateral midbrain tegmentum and parts of the pons [27,44]. Out of these, only PAG lesions caused mutism. None of the lesions led to a deterioration of vocal structure (dysphonia). A number of studies tested the effects of lesions on vocalization electrically elicited from the PAG [27,29,46,56]. Lesions capable of blocking PAG-elicited vocalizations follow the same course as the sites producing vocalization when electrically stimulated, that is, they can be traced from the PAG through the laterally adjacent caudodorsal midbrain tegmentum and along the lateral lemniscus into the ventrolateral pons; from here the effective lesions continue through the lateral medulla down to the nucleus retroambiguus and surrounding reticular formation. PAG-elicited vocalizations, in addition, can be blocked by interrupting the somatosensory feedback from the pulmonary stretch receptors into the solitary tract nucleus, making clear that the vocal pattern generator depends upon an input from the solitary tract nucleus [9,41].

Blocking of PAG-elicited vocalization by pharmacological inactivation of lower brainstem structures has been reported in

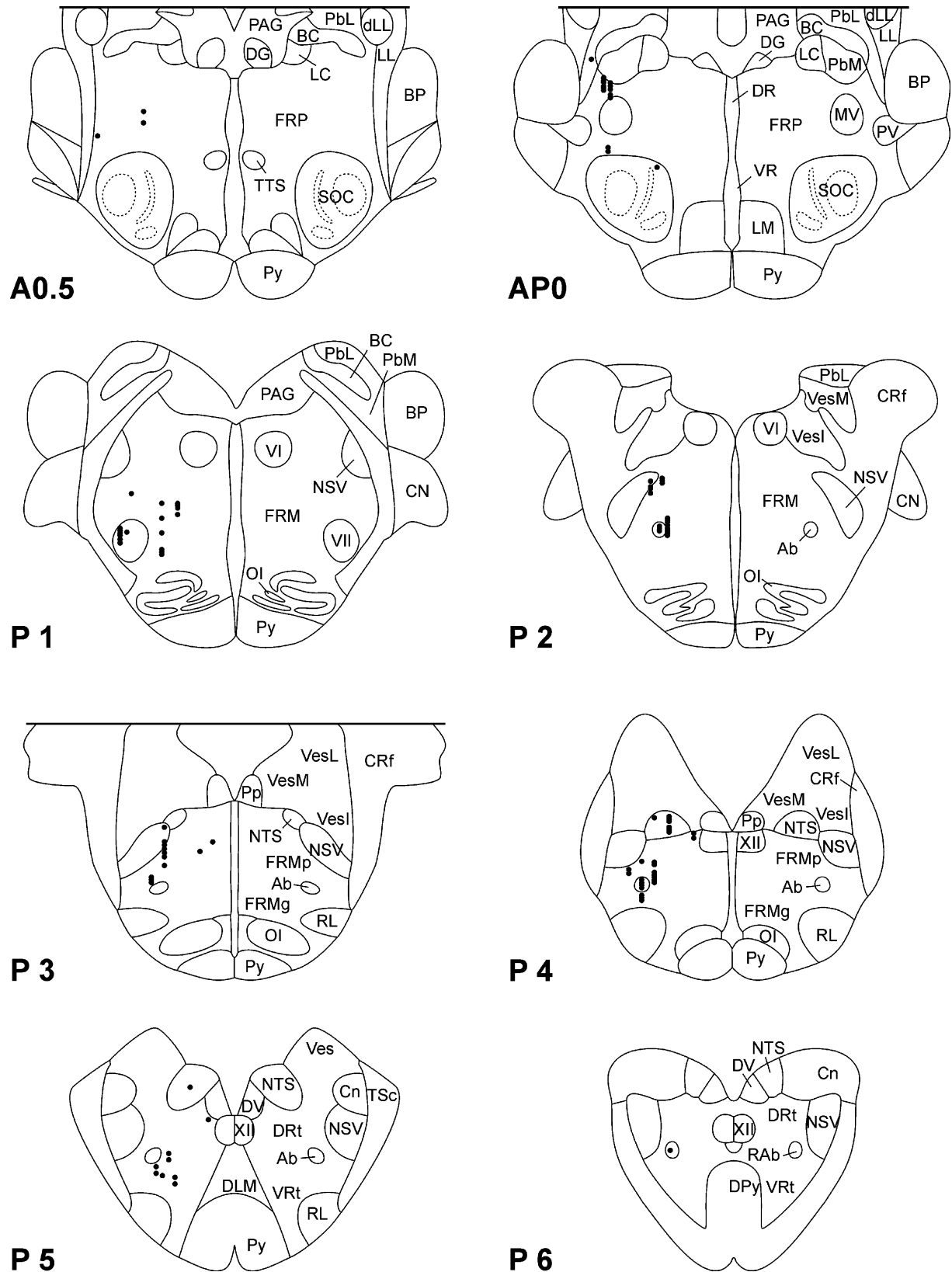


Fig. 1. Distribution of neurons in the squirrel monkey's brainstem with vocalization-correlated activity. All neurons shown start firing before vocalization onset and change their discharge rate with changes in fundamental frequency and/or amplitude. The numbers in the lower left corner indicate the stereotactic frontal planes, according to Emmers and Akert [13]. For abbreviations, see Abbreviation list.

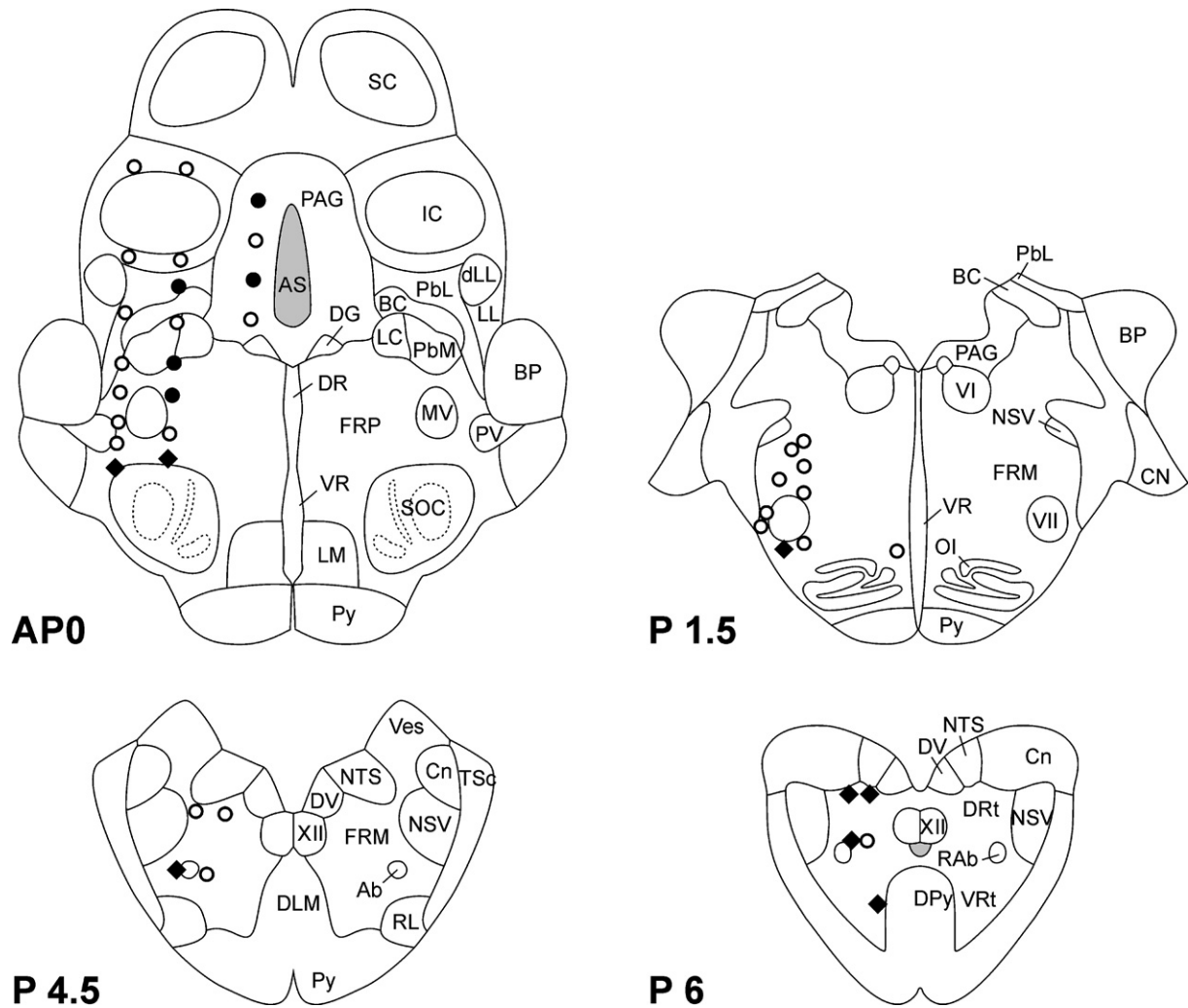


Fig. 2. Frontal sections of the squirrel monkey's brainstem, showing sites producing vocalization when electrically or pharmacologically stimulated. Open circles represent sites producing vocalization exclusively with electrical stimulation. Black circles represent sites at which electrical as well as glutamatergic stimulation produces normal species-specific calls. Black rhombs represent sites at which electrical as well as glutamatergic stimulation produces abnormal vocalization. The numbers in the lower left corner indicate the stereotaxic frontal planes, according to Emmers and Akert [13]. For abbreviations, see Abbreviation list.

three studies. Shiba et al. [46] found that inactivation of the nucleus retroambiguus and surrounding reticular formation with kainic acid abolished PAG-elicited vocalization in the cat. In the squirrel monkey, PAG vocalization could be blocked by injecting the glutamate antagonist kynurenic acid into the periolivary region in the ventrolateral pons [23]. In this case, however, only a specific class of vocalizations could be blocked, namely vocalizations showing a characteristic frequency modulation (“trill”, “chatter”, “cackle”). Other call types which lack such a modulation (“squeal”, “peep”, “caw”, “shriek”, “spitting”, “growl”) remained unaffected. A similar finding is reported by Fenzl and Schuller [16] for the bat. From the bat's PAG, echolocation as well as social calls can be elicited. Injection of kynurenic acid into the paralemnisal area abolishes echolocation calls, but leaves social calls unaffected. As pharmacological inactivations, similar to pharmacological stimulations, affect only synaptic regions and cell bodies, not by-passing fibers, such studies are better than electrical lesion studies suited to pinpoint sites of vocal processing. The studies indicate that the paralem-

niscal and periolivary pontine regions play a crucial role in the production of specific call types, while the region around the nucleus retroambiguus seems to be involved in vocal production in a more general way. The findings further suggest that pattern generation of different call types might take place in different regions.

### 3.4. Anatomical data

Vocalization depends on a coordinated activity of internal and external laryngeal muscles, abdominal and intercostal expiratory muscles and numerous articulatory muscles, controlling lips, tongue, velum and jaw. The corresponding motoneurons are distributed over the nucleus ambiguus, a small retro-hypoglossal cell column, the ventral horn of the thoracic and upper lumbar cord, the facial, hypoglossal and trigeminal motor nuclei [24]. Theoretically, there are two possibilities in which way the various motoneuron pools involved in phonation could be coordinated in their activity. One possibility is that all phonatory



motoneuron pools are connected with each other directly, and in this way coordinate their activity. The other is that there are one or several superordinate structures with direct connections to all phonatory motoneuron pools, that is, trigeminal, facial, hypoglossal, ambigular and spinal ones, controlling them in a hierarchical way. Neuroanatomical studies have shown that there is an almost complete lack of direct interconnections between the phonatory motor nuclei; those few interconnections that have been found were by interneurons, not motoneurons, of the phonatory motor nuclei [8,15,36,52]. On the other hand, there is an extensive region outside of the phonatory motoneuron pools, having direct connections with all the phonatory motoneuron pools conjointly. This region includes the lateral parabrachial area, the parvocellular reticular formation just above the superior olive, the lateral medullary reticular formation and the dorsal and ventral reticular nuclei, together with the nucleus retroambiguus in the caudalmost part of the medulla [4,15,20,51,53]. Double-labeling studies have shown that many cells in these structures project to more than one motor nucleus and contact the motor nuclei bilaterally [8,31,32]. All structures with common input to the phonatory motor nuclei receive a direct input from the PAG [37,42]. All structures also receive a direct input from the solitary tract nucleus [3,17], providing these structures with the proprioceptive information from lungs, larynx and oral cavity necessary for the production of normal vocalization [25,47,50].

With respect to the nucleus retroambiguus, a special comment seems to be in place. From the fact that the nucleus retroambiguus receives a heavy input from the PAG, that injection of an anterograde tracer into the region of the nucleus retroambiguus produces labeling in all phonatory motor nuclei, and that lesions destroying the retroambiguus region block PAG-elicited vocalization, Holstege [21] concluded that the nucleus retroambiguus represents an obligatory relay station of the descending PAG vocalization pathway, controlling directly all motoneuron pools involved in phonation. More recent anatomical studies have made clear, however, that the nucleus retroambiguus does not have direct connections with the trigeminal motor, facial and hypoglossal nuclei [8,15,52]. 96% of the retroambiguus neurons are bulbospinal neurons without medullary collaterals [14,38]. Many of these make direct contact with expiratory motoneurons in the thoracic and upper lumbar ventral horn [5,6,53]. The only cranial phonatory motor nucleus receiving a direct input from the nucleus retroambiguus is the nucleus ambiguus [7,54]. On the other hand, the dorsal reticular nucleus just above the nucleus retroambiguus does have projections to the trigeminal motor, facial and hypoglossal nuclei as well as to the nucleus ambiguus and into the ventral horn of the thoracic and lumbar spinal cord [4,8,51,53,55]. Part of the projections attributed by Holstege [21] to the nucleus retroambiguus, thus were due to spill-over of the tracer into the dorsal reticular nucleus. Also the finding of Shiba et al. [46], that injection of kainic acid into the region of the nucleus retroambiguus abolished PAG-elicited vocalization and vocal fold movements, might be explained in this way. The injections in their study invaded the dorsal reticular nucleus and thus can not answer the question of whether the lesion effects were due to a destruction of the nucleus retroambiguus, the surrounding reticular formation or of both together. There is general

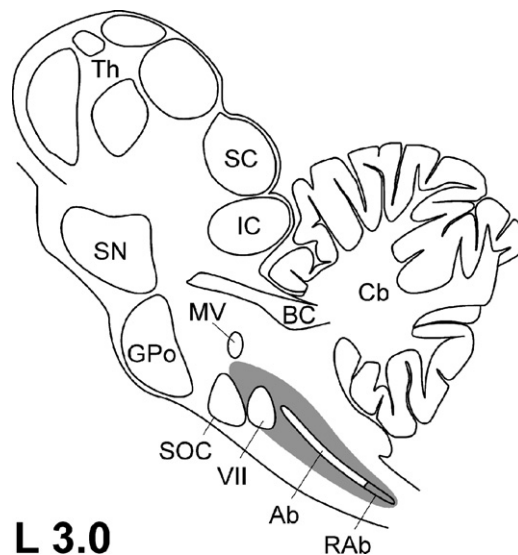


Fig. 3. Sagittal section of the squirrel monkey's brainstem at 3 mm lateral to the midline, indicating the proposed area for vocal pattern generation (gray shading). For abbreviations, see Abbreviation list.

agreement, however, that the nucleus retroambiguus contains the highest concentration of expiratory pre-motoneurons in the brainstem, pointing to a crucial role of this nucleus in the control of the respiratory component of vocalization.

#### 4. Conclusion

At the beginning of this review, a number of criteria were listed which were considered characteristic of a vocal pattern generator. Structures which, according to the currently available data, fulfil all these criteria are the parvocellular pontine reticular formation just above the superior olive, the reticular formation around facial nucleus and nucleus ambiguus, and the region around the nucleus retroambiguus, including the dorsal and ventral reticular nuclei together with the nucleus retroambiguus itself (Fig. 3). All these regions seem to be involved in vocal pattern generation. Future work will have to clarify which specific functions are fulfilled by which subregions.

#### References

- [1] Bandler R, Carrive P. Integrated defence reaction elicited by excitatory amino acid microinjection in the midbrain periaqueductal grey region of the unrestrained cat. *Brain Res* 1988;439:95–106.
- [2] Bazett HC, Penfield WG. A study of the Sherrington decerebrate animal in the chronic as well as the acute condition. *Brain* 1922;45:185–265.
- [3] Beckstead RM, Morse JR, Norgren R. The nucleus of the solitary tract in the monkey: projections to the thalamus and brain stem nuclei. *J Comp Neurol* 1980;190:259–82.
- [4] Bernard JF, Villanueva L, Carroue J, Le Bars D. Efferent projections from the subnucleus reticularis dorsalis (SRD): a *Phaseolus vulgaris* leucoagglutinin study in the rat. *Neurosci Lett* 1990;116:257–62.
- [5] Billig I, Hartge K, Card JP, Yates BJ. Transneuronal tracing of neural pathways controlling abdominal musculature in the ferret. *Brain Res* 2001;912:24–32.
- [6] Boers J, Kirkwood PA, De Weerd H, Holstege G. Ultrastructural evidence for direct excitatory retroambiguus projections to cutaneous trunci and abdominal external oblique muscle motoneurons in the cat. *Brain Res Bull* 2006;68:249–56.

- [7] Boers J, Klop EM, Hulshoff AC, De Weerd H, Holstege G. Direct projections from the nucleus retroambiguus to cricothyroid motoneurons in the cat. *Neurosci Lett* 2002;319:5–8.
- [8] Cunningham ET, Sawchenko PE. Dorsal medullary pathways subserving oromotor reflexes in the rat: implications for the central neural control of swallowing. *J Comp Neurol* 2000;417:448–66.
- [9] Davis PJ, Zhang SP, Bandler R. Pulmonary. upper airway afferent influences on the motor pattern of vocalization evoked by excitation of the midbrain periaqueductal gray of the cat. *Brain Res* 1993;607:61–80.
- [10] Davis PJ, Zhang SP, Bandler R. Midbrain and medullary regulation of respiration and vocalization. In: Holstege G, Bandler R, Saper C, editors. *The emotional motor system*. Progress in brain research, vol. 107. Amsterdam: Elsevier; 1996. p. 315–25.
- [11] Depaulis A, Bandler R, Vergnes M. Characterization of pretentorial periaqueductal gray matter neurons mediating intraspecific defensive behaviors in the rat by microinjections of kainic acid. *Brain Res* 1989;486:121–32.
- [12] Düsterhöft F, Häusler U, Jürgens U. Neuronal activity in the periaqueductal gray and bordering structures during vocal communication in the squirrel monkey. *Neuroscience* 2004;123:53–60.
- [13] Emmers R, Akert K. A stereotaxic atlas of the brain of the squirrel monkey (*Saimiri sciureus*). Madison: University of Wisconsin Press; 1963.
- [14] Ezure K, Tanaka I, Saito Y. Brainstem and spinal projections of augmenting expiratory neurons in the rat. *Neurosci Res* 2003;45:41–51.
- [15] Fay RA, Norgren R. Identification of rat brainstem multisynaptic connections to the oral motor nuclei in the rat using pseudorabies virus. *Brain Res Rev* 1997;25:255–311.
- [16] Fenzl T, Schuller G. Echolocation calls and communication calls are controlled differentially in the brainstem of the bat *Phyllostomus discolor*. *BMC Biol* 2005;3:17.
- [17] Gerrits PO, Holstege G. Pontine and medullary projections to the nucleus retroambiguus: a wheat germ agglutinin horseradish peroxidase and autoradiographic tracing study in the cat. *J Comp Neurol* 1996;373:173–85.
- [18] Hage SR, Jürgens U. On the role of the pontine brainstem in vocal pattern generation. A telemetric single-unit recording study in the squirrel monkey. *J Neurosci* 2006;26:7105–15.
- [19] Hammerschmidt K, Freudenstein T, Jürgens U. Vocal development in squirrel monkeys. *Behaviour* 2001;138:1179–204.
- [20] Hannig S, Jürgens U. Projections of the ventrolateral pontine vocalization area in the squirrel monkey. *Exp Brain Res* 2006;169:92–105.
- [21] Holstege G. Anatomical study of the final common pathway for vocalization in the cat. *J Comp Neurol* 1989;284:242–52.
- [22] Jürgens U. The role of the periaqueductal grey in vocal behaviour. *Behav Brain Res* 1994;62:107–17.
- [23] Jürgens U. Localization of a pontine vocalization-controlling area. *J Acoust Soc Am* 2000;108:1393–6.
- [24] Jürgens U. Neural pathways underlying vocal control. *Neurosci Biobehav Rev* 2002;26:235–58.
- [25] Jürgens U, Kirzinger A. The laryngeal sensory pathway and its role in phonation. A brain lesioning study in the squirrel monkey. *Exp Brain Res* 1985;59:118–24.
- [26] Jürgens U, Ploog D. Cerebral representation of vocalization in the squirrel monkey. *Exp Brain Res* 1970;10:532–54.
- [27] Jürgens U, Pratt R. Role of the periaqueductal grey in vocal expression of emotion. *Brain Res* 1979;167:367–78.
- [28] Jürgens U, Richter K. Glutamate-induced vocalization in the squirrel monkey. *Brain Res* 1986;373:349–58.
- [29] Kirzinger A, Jürgens U. The effects of brainstem lesions on vocalization in the squirrel monkey. *Brain Res* 1985;358:150–62.
- [30] Larson CR. On the relation of PAG neurons to laryngeal and respiratory muscles during vocalization in the monkey. *Brain Res* 1991;552:77–86.
- [31] Li YQ, Takada M, Mizuno N. Identification of premotor interneurons which project bilaterally to the trigeminal motor, facial or hypoglossal nuclei. A fluorescent retrograde double-labeling study in the rat. *Brain Res* 1993;611:160–4.
- [32] Li YQ, Takada M, Mizuno N. Premotor neurons projecting simultaneously to 2 orofacial motor nuclei by sending their branched axons. A study with a fluorescent retrograde double-labeling technique in the rat. *Neurosci Lett* 1993;152:29–32.
- [33] Lu C-L, Jürgens U. Effects of chemical stimulation in the periaqueductal gray on vocalization in the squirrel monkey. *Brain Res Bull* 1993;32:143–51.
- [34] Lüthe L, Häusler U, Jürgens U. Neuronal activity in the medulla oblongata during vocalization. A single-unit recording study in the squirrel monkey. *Behav Brain Res* 2000;116:197–210.
- [35] Magoun HW, Atlas D, Ingersoll EH, Ranson SW. Associated facial, vocal and respiratory components of emotional expression: an experimental study. *J Neurol Psychopathol* 1937;17:241–55.
- [36] Manaker S, Tischler LJ, Bigler TL, Morrison AR. Neurons of the motor trigeminal nucleus project to the hypoglossal nucleus in the rat. *Exp Brain Res* 1992;90:262–70.
- [37] Mantyh PW. Connections of midbrain periaqueductal gray in the monkey. *J Neurophysiol* 1983;49:567–94.
- [38] Merrill EG, Lipski J. Inputs to intercostal motoneurons from ventrolateral medullary respiratory neurons in the cat. *J Neurophysiol* 1987;57:1837–53.
- [39] Metzner W. An audio-vocal interface in echolocating horseshoe bats. *J Neurosci* 1993;13:1899–915.
- [40] Monnier M, Willi H. Die integrative Tätigkeit des Nervensystems beim meso-rhombospinalen Anencephalus (Mittelhirnwesen). *Monatsschr Psychiatr Neurol* 1953;126:239–73.
- [41] Nakazawa K, Shiba K, Satoh I, Yoshida K, Nakajima Y, Konno A. Role of pulmonary afferent inputs in vocal on-switch in the cat. *Neurosci Res* 1997;29:49–54.
- [42] Odeh F, Antal M. The projections of the midbrain periaqueductal grey to the pons and medulla oblongata in rats. *Eur J Neurosci* 2001;14:1275–86.
- [43] Pieper F, Jürgens U. Neuronal activity in the inferior colliculus and bordering structures during vocalization in the squirrel monkey. *Brain Res* 2003;979:153–64.
- [44] Randall WL. The behavior of cats (*Felis catus*) with lesions in the caudal midbrain region. *Behaviour* 1964;23:107–39.
- [45] Scheiner E, Hammerschmidt K, Jürgens U. The influence of hearing impairment on the preverbal emotional vocalization of infants. *Folia Phoniat Logopaed* 2004;56:27–40.
- [46] Shiba K, Umezaki T, Zheng Y, Miller AD. The nucleus retroambiguus controls laryngeal muscle activity during vocalization in the cat. *Exp Brain Res* 1997;115:513–9.
- [47] Shiba K, Yoshida K, Miura T. Functional roles of the superior laryngeal nerve afferents in electrically induced vocalization in anesthetized cats. *Neurosci Res* 1995;22:23–30.
- [48] Siebert S, Jürgens U. Vocalization after periaqueductal grey inactivation with the GABA agonist muscimol in the squirrel monkey. *Neurosci Lett* 2003;340:111–4.
- [49] Siebert S, Schuller G. Vocalization in bats: interactions between periaqueductal grey and nucleus of the brachium of the inferior colliculus. *FENS Abstr* 2006;3:A 040.4.
- [50] Thoms G, Jürgens U. Role of the internal laryngeal nerve in phonation: an experimental study in the squirrel monkey. *Exp Neurol* 1981;74:187–203.
- [51] Thoms G, Jürgens U. Common input of the cranial motor nuclei involved in phonation in squirrel monkey. *Exp Neurol* 1987;95:85–99.
- [52] Travers JB, Yoo J-E, Chandran R, Herman K, Travers SP. Neurotransmitter phenotypes of intermediate zone reticular formation projections to the motor trigeminal and hypoglossal nuclei in the rat. *J Comp Neurol* 2005;488:28–47.
- [53] VanderHorst VGJM, Terasawa E, Ralston HJ, Holstege G. Monosynaptic projections from the nucleus retroambiguus to motoneurons supplying the abdominal wall, axial, hindlimb, and pelvic floor muscles in the female rhesus monkey. *J Comp Neurol* 2000;424:233–50.
- [54] VanderHorst VGJM, Terasawa E, Ralston HJ. Monosynaptic projections from the nucleus retroambiguus region to laryngeal motoneurons in the rhesus monkey. *Neuroscience* 2001;107:117–25.
- [55] Zhang JD, Luo PF. Ultrastructural features of synapse from dorsal parvocellular reticular formation neurons to hypoglossal motoneurons of the rat. *Brain Res* 2003;963:262–73.
- [56] Zhang SP, Bandler R, Davis PJ. Brain stem integration of vocalization: role of the nucleus retroambiguus. *J Neurophysiol* 1995;74:2500–12.