

Topographic projections from the periamygdaloid cortex to select subregions of the lateral nucleus of the amygdala in the rat

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Received 22 March 1996; revised version received 21 May 1996; accepted 23 May 1996

Abstract

Information from most of the sensory modalities enters the amygdala via the lateral nucleus. The olfactory information, however, arrives at the amygdala through the superficial nuclei, including the periamygdaloid cortex. To find out whether the olfactory information can modulate the processing of sensory information in the lateral nucleus we injected *Phaseolus vulgaris* leucoagglutinin, an anterograde axonal tracer, into the different divisions of the periamygdaloid cortex. We found that the PAC division of the periamygdaloid cortex projects to the ventrolateral and medial divisions, but not the dorsolateral division, of the lateral amygdaloid nucleus. Therefore, the projection from the PAC to the lateral nucleus provides a route, by which the olfactory information may become associated with other sensory modalities. Also, together with our previous finding that the lateral nucleus projects to the periamygdaloid cortex, the present data demonstrate that the lateral nucleus and the PAC are reciprocally connected.

Keywords: Anatomy; Anterograde tracer; Emotional memory; Olfaction; Temporal lobe

The lateral nucleus is a major sensory receptive region of the amygdala [6,7,14]. It receives somatosensory, auditory, and visual inputs from both thalamic and cortical areas [2,7,9,14,15,19]. By way of topographically organized intra-amygdaloid connections [12], sensory information is conveyed from the lateral nucleus to several other amygdaloid regions, and is eventually channeled to extra-amygdaloid areas that control responses appropriate to the emotional significance of sensory events processed by the lateral nucleus [6].

While it has long been assumed that information flow in the amygdala is fairly unidirectional, we recently found that the lateral nucleus receives inputs from two of its major intra-amygdaloid targets, i.e. from the basal and accessory basal nuclei [13,16,17]. These connections may provide a route by which inputs from the frontal cortex and hippocampal formation might modulate early steps of information processing occurring in the lateral nucleus.

One of the main exceptions to the rule that sensory inputs enter the amygdala by way of the lateral nucleus is

the fact that inputs from the olfactory bulb and olfactory cortex terminate in the periamygdaloid cortex [14]. Interestingly, the periamygdaloid cortex also receives a substantial input from the lateral nucleus [12]. The present study investigates whether the periamygdaloid cortex, like the basal and accessory basal nuclei, sends projections back to the lateral nucleus. If so, a route would exist by which olfactory information could modulate the processing of sensory information from other modalities in the lateral nucleus.

Four male Sprague–Dawley rats and two male Wistar rats were used in this study. The solution containing 2.5% *Phaseolus vulgaris* leucoagglutinin (PHA-L) in 0.1 M sodium phosphate buffer (pH 7.4) was injected iontophoretically into different divisions of the periamygdaloid cortex. After a survival period of 10–14 days, the animals were deeply anesthetized and perfused for immunohistochemistry. For a detailed description of the procedures used for fixation and PHA-L immunohistochemistry, see Ref. [16].

We used a nomenclature modified from Price et al. [14] for the rat amygdala [16]. The lateral nucleus includes three divisions, the dorsolateral, ventrolateral, and

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medial divisions (see Figs. 1,2). The periamygdaloid cortex is composed of three divisions, PAC (periamygdaloid cortex), PACm (medial division of the periamygdaloid cortex) and PACs (sulcal division of the periamygdaloid cortex) (see Fig. 1). In the nomenclature used in the present study, the PAC and PACm divisions of the periamygdaloid cortex correspond mostly to 'the lateral zone of the posterior part of the posterior cortical nucleus', and the PACs division to the 'piriform-amygdaloid area' of the nomenclature of Swanson [18]. Paxinos and Watson [11] included all divisions of the periamygdaloid cortex into 'the posterolateral cortical nucleus'. Alheid et al. [1], in turn, called the PAC as 'the oral medial and caudal lateral subgroups of the posterolateral cortical nucleus' and the PACm as 'the caudal medial subgroup of the posterolateral cortical nucleus', the PACs was mostly included into 'the caudal lateral subgroup of the posterolateral cortical nucleus' (see Fig. 15 in Ref. [1]).

In six animals the PHA-L injection was located in the periamygdaloid cortex. Injections ABM4, ABM5, and ABM6 were located mostly in layer II of the PAC (Fig. 1), although ABM6 was also involved in layer II of the

PACm. Injection ABM27 was also located in layer II of the PACm (Fig. 1). R66–93 was located mostly in layer II and R75–93 in layer III of the PACs. Only a few labeled neurons were found in other regions (a few labeled neurons in the accessory basal nucleus and in the piriform cortex in ABM5, in the piriform cortex in ABM4 and ABM6, and in the amygdalopiriform transition area in R66–93 and R75–93).

The PAC sends a substantial projection to both the medial and ventrolateral divisions of the lateral amygdaloid nucleus (Fig. 2). In two cases (ABM5 and ABM6) the projection was slightly heavier in the ventrolateral division than in the medial division. In general, the projection to the ventrolateral division is heavy throughout its rostrocaudal extent (Fig. 2), while PAC projections to the medial division are more dense caudally. In the dorso-lateral division, we observed only straight and sparsely varicose fibers which resemble fibers en passage. The PACm and PACs do not appear to project to the lateral nucleus.

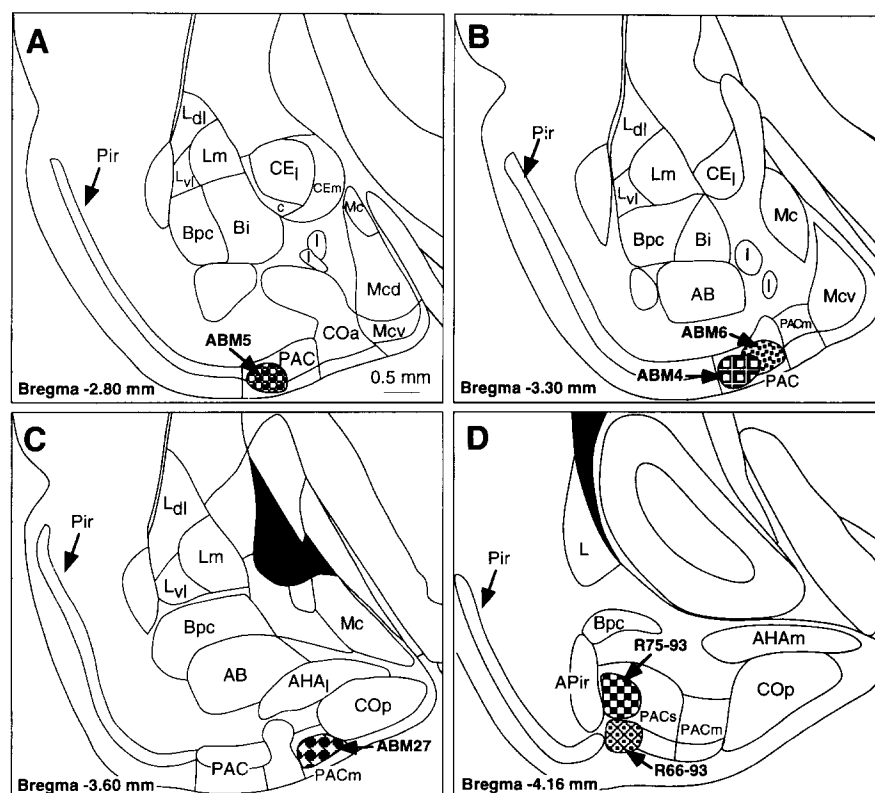


Fig. 1. Line drawings from four different rostrocaudal levels of the rat amygdala. The different shading patterns indicate the location of PHA-L injection sites in different divisions of the periamygdaloid cortex. Abbreviations: AB, accessory basal nucleus; AHA_l, amygdalohippocampal area, lateral division; AHA_m, amygdalohippocampal area, medial division; APir, amygdalopiriform transition area; Bi, basal nucleus, intermediate division; Bmc, basal nucleus, magnocellular division; Bpc, basal nucleus, parvocellular division; c, central nucleus, capsular division; CE_l, central nucleus, lateral division; CEm, central nucleus, medial division; CO_a, anterior cortical nucleus; CO_p, posterior cortical nucleus; I, intercalated nucleus; L_{dl}, lateral nucleus, dorsolateral division; Lm, lateral nucleus, medial division; L_{vl}, lateral nucleus, ventrolateral division; Mc, medial nucleus, caudal division; Mcd, medial nucleus, dorsal portion of the central division; Mcv, medial nucleus, ventral portion of the central division; PAC, periamygdaloid cortex; PACm, periamygdaloid cortex, medial division; PACs, periamygdaloid cortex, sulcal division; Pir, piriform cortex.

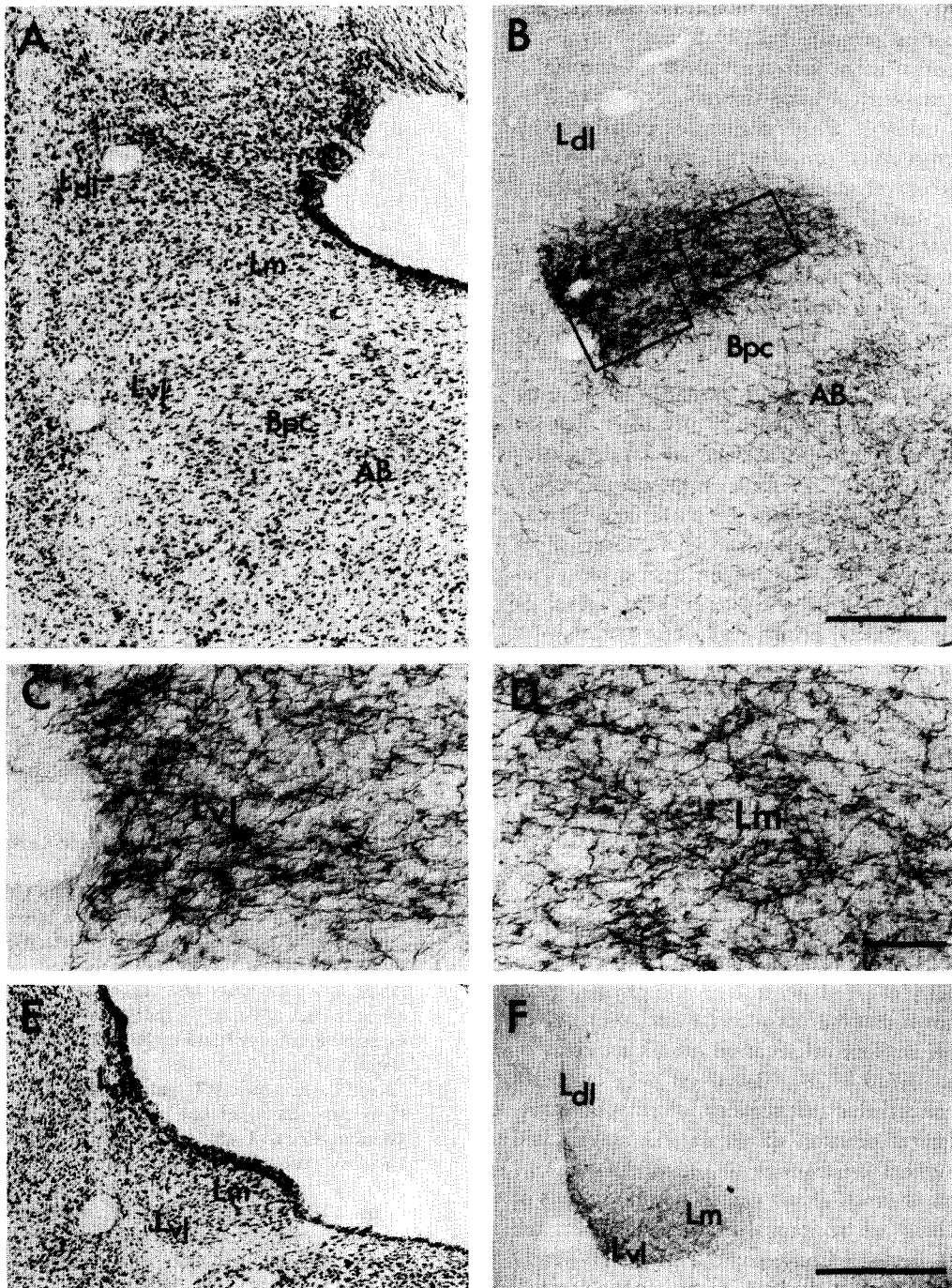


Fig. 2. Photomicrographs demonstrating terminal labeling in the medial and ventrolateral divisions of the lateral nucleus after PHA-L injection into the PAC (case ABM5). (A) A brightfield photomicrograph of a Nissl-stained section. (B) A brightfield photomicrograph of an adjacent section stained for PHA-L. (C,D) Higher magnification photomicrographs taken with Nomarski optics from the areas outlined in (B), (C) is from the ventrolateral and (D) is from the medial division of the lateral nucleus. (E) A brightfield photomicrograph of a Nissl-stained section and (F) is of an adjacent section stained for PHA-L demonstrating the terminal labeling in the caudal portion of the lateral nucleus. Note that the dorsolateral division of the lateral nucleus contains only few labeled fibers. Abbreviations as in Fig. 1. Scale bars: (A,B,E,F), 500 μ m; (C,D), 100 μ m.

Information processing in the amygdala is traditionally considered to be quite unidirectional [2,14]. According to this idea, the basal, accessory basal, medial, central nuclei, and the periamygdaloid cortex, all of which receive inputs from the lateral nucleus [12], send very few, if any,

projections back to the lateral nucleus. Contrary to this hypothesis, we recently reported that the lateral nucleus is reciprocally connected with the basal and accessory basal nuclei [13,16,17]. Furthermore, Canteras et al. [5] showed that the medial nucleus projects to the lateral nucleus. In

the present study, we further demonstrate that the periamygdaloid cortex projects heavily to the lateral nucleus. Similar observations were previously mentioned in the studies of Ottersen [10] and Canteras et al. [4]. The present study extends these earlier observations by showing that projections from the periamygdaloid cortex are directed exclusively to the ventrolateral and medial divisions of the lateral nucleus and that they originate only from the PAC (and not from the PACm or PACs division) of the periamygdaloid cortex. Thus, the lateral nucleus is reciprocally connected with several of its intra-amygdaloid target regions, including the periamygdaloid cortex.

These reciprocal projections may provide pathways by which different amygdaloid nuclei modify their own inputs. They may also provide a route by which extra-amygdaloid afferents to these nuclei influence the early steps of information processing in the amygdala. For example, the periamygdaloid cortex receives a direct input from the olfactory bulb [14] and from the piriform and entorhinal cortices [14]. Since the lateral nucleus receives little information from the primary olfactory cortex [14], the periamygdaloid cortex may provide the major source of olfactory input to the lateral nucleus. Olfactory information arriving at the lateral nucleus via the periamygdaloid cortex may, therefore, converge with sensory information coming from other modalities in the ventrolateral and medial divisions of the lateral nucleus.

The present study indicates that the dorsolateral division of the lateral nucleus does not receive projections from the PAC. Interestingly, the dorsolateral division does not receive projections from the other divisions of the lateral nucleus either [12] or from the basal or accessory basal nuclei [16,17]. Tract-tracing and physiological studies have shown that the dorsolateral division receives mainly unimodal sensory information from sensory associative cortices [3,7–9,15,19]. Based on data currently available it is conceivable that sensory information entering the dorsolateral division of the lateral amygdaloid nucleus is not subject to intra-amygdaloid modulation.

In conclusion, the medial and ventrolateral divisions of the lateral nucleus are reciprocally connected with the periamygdaloid cortex. Consequently, relatively early phases of information processing within the amygdala may be subject to modulation by other amygdaloid nuclei through their reciprocal connections with the lateral nucleus.

The authors wish to thank Ms. Merja Lukkari for excellent histological assistance and Ms. Eija Antikainen for photographic processing. This study was financially supported by the Academy of Finland and the Vaajasalo Foundation (A.P.) and by USPHS grants MH 38774, MH 46516 and MH 00956 (J.E.L.)

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