Electrophysiological Evidence for a Topographical Projection of the Nasal Mucosa onto the Olfactory Bulb of the Frog

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ABSTRACT Three olfactory nerve branches respectively subserving either a medial, an intermediate, or a lateral region of the dorsal olfactory receptor sheet of the bullfrog Rana catesbeiana were electrically stimulated with bipolar platinum hook electrodes. Extracellular single unit responses from 93 second-order cells in different regions of the olfactory bulb were recorded with metal-filled glass micropipets. The excitatory responsiveness of each unit to the stimulation of each of the three nerve branches (response profile) was determined. Some units were sensitive to stimulation of each of the three nerve branches, thus suggesting a wide projection from the entire receptor sheet. On the other hand, other units were more selective. Of this latter group, units in the lateral bulb were excited by nerve branches subserving the more lateral regions of the receptor sheet; units in the medial bulb were excited by the nerve branches subserving the more medial regions of the receptor sheet. These data provide electrophysiological evidence for a topographical projection of the olfactory receptor sheet onto the olfactory bulb, and further suggest that the projections onto different bulbar cells vary in degree of localization.

INTRODUCTION

On the basis of his recordings of multiunit discharges in different anterior-posterior regions of the olfactory bulb in rabbit and cat in response to different odorants, Adrian (1951, 1953, and 1954) introduced the concept of differential spatial and temporal patterns of neural activity as one of the mechanisms that could underlie odorant discrimination. Adrian reasoned that the different spatial and temporal patterns he observed at the level of the olfactory bulb must reflect similar precursory spatiotemporal patterns of neural activity at the level of the olfactory receptor sheet. A subsequent histological investigation using retrograde degeneration techniques (Le Gros Clark, 1951) reversed the conclusion of an earlier, less extensive study (Le Gros Clark and Warwick, 1946) by demonstrating at least a loose topographical projection of the olfactory epithelium onto the olfactory bulb. Although this projection was found to be more precise along a dorsoventral axis than in the anteroposterior direction empha-
sized by Adrian and although some of the projections seemed rather diffuse, this histological evidence did, nevertheless, give credence to the concept of a topographical representation of the epithelium in the bulb. More recent studies using modern anterograde tracing techniques (Land et al., 1973; Land and Shepherd, 1974) have given further support for the existence of a topographical projection, albeit along spatial directions not emphasized by Adrian. In these recent studies the dorsal recess of the nasal cavity was found to project to the dorsal aspect of the bulb whereas the lateral region of the nasal cavity projected to the lateral part of the bulb. In addition, these studies showed that there were regional differences in the degree of “sharpness” of these projections, ranging from precise to rather diffuse.

Freeman (1974) chose to emphasize the diffuseness of the projection of the mucosa onto the bulb while still acknowledging some topographic organization. This emphasis was based upon his analysis of evoked bulbar potentials produced by the electrical stimulation of a pool of olfactory nerve axons. Since each of the evoked potentials could be recorded over much of the bulbar surface, he concluded that the receptors in each part of the mucosa must influence glomeruli over very broad regions of the bulb. Nevertheless, Freeman did observe that changes in the position of the stimulating electrodes in the population of olfactory nerve axons did produce shifts in the epicenters of these widely recorded evoked potentials. He therefore concluded that on the average there is a topographic organization of the population of olfactory nerve axons but not of the point-to-point variety.

From Adrian's work two mechanisms by which different spatiotemporal patterns might be established at the level of the receptor sheet are suggested: (a) the receptor cells might have differential selective sensitivities to different odorants (Gesteland et al., 1963; Mathews and Tucker, 1966; Mathews, 1972; O'Connell and Mozell, 1969) and receptors with like sensitivity might be clustered together into regional aggregates across the receptor sheet (Kauer and Moulton, 1974); (b) regardless of the selective sensitivity of the receptors per se, different patterns of neural activity might result as a consequence of differences in the sorption of odorant molecules across the mucosal sheet. Those odorants which are differentially sorbed would give rise to different odorant distribution patterns across the olfactory mucosa and thus different patterns of activity across the receptor sheet. Either or both of these mechanisms could project different regional and temporal patterns of excitation into the olfactory bulb as different odorants pass over the receptor sheet.

Although Mozell and Pfaffmann (1954) and Mozell (1958) have confirmed the differential spatiotemporal patterns that Adrian observed in the bulb, there was for some time no direct evidence from the olfactory mucosa itself to support Adrian's suggestion of spatiotemporal patterns at the peripheral level. Such evidence has been presented by Mozell (1964, 1966, 1970). He compared, for different odorants, the responses of two branches of the olfactory nerve which sampled the activity of two widely separated regions of the olfactory mucosa. He observed that both the relative magnitude of the responses of these two nerve branches and the differences in their latencies varied characteristically from chemical to chemical. Mozell proposed that these various space-time activity
patterns reflected the differential sorption (and consequently the differential distribution) of the molecules of different odorants across the mucosa. Mozell and his co-workers later presented more direct evidence for differential molecular distributions by chromatographically measuring the mucosal retention times of different odorants in the intact olfactory sac (Mozell and Jagodowicz, 1973) and by mapping the distribution of tritiated odorant molecules across the mucosa (Hornung et al., 1975).

In addition, recent data have been interpreted as evidence for regional aggregates of receptors with similar selective sensitivities (Mustaparta, 1970; Kauer and Moulton, 1974). Of particular interest in this regard is Kauer and Moulton's study of single units in the olfactory bulb of salamander in response to punctate stimulation of the olfactory mucosa. Some mucosal regions appeared more responsive to some chemicals than did others. This result seemed consistent with the results of Moulton's earlier studies (1963, 1965, 1967) involving multiunit discharges in the rabbit olfactory bulb. Using an array of electrodes recording from a mosaic of positions in the bulb, Moulton noted that the pattern of discharge magnitudes across this mosaic differed for different chemicals. Moulton later (Pfaffmann, 1969) interpreted these data as being based upon a mosaic of epithelial regions in which the receptors of any one region have the same sensitivity but the receptors in different regions have different sensitivities.

Thus there appears to be evidence for two mechanisms which could underlie the spatiotemporal analysis of odorants at the receptor level, i.e. aggregates of selectively sensitive receptors and differential molecular distributions. It is important to note, as indicated by Mozell (1971), that these two mechanisms are not mutually exclusive and could indeed operate in concert to produce a much greater range of spatiotemporal patterns than could either mechanism alone.

Regardless of whether one or both of the proposed mechanisms is responsible for the activity patterns established at the mucosa, it seems critical to understand how the pattern may be preserved and transferred to cells at higher levels of the olfactory system. In other sensory systems such preservation is accomplished by the display of a topographical projection of the receptor sheet at more central levels of the system (Mountcastle, 1957; Hubel and Wiesel, 1962, 1965, 1968). The present experiments were designed to test for the existence of a similar topographical projection of the olfactory receptor sheet onto the second order neurons in the olfactory bulb.

METHODS

Preparation

Louisiana bullfrogs *Rana catesbeiana* were immobilized with a subcutaneous injection of *d*-tubocurarine (30 mg/kg), wrapped in a moist towel, and placed in an ear-bar head holder to fix the head firmly in place. Anesthesia for all surgical procedures was provided by topical application of 5% procaine hydrochloride. The bone and cartilage overlying the olfactory bulbs and the dorsal aspect of the olfactory sac were removed. This allowed access to the branches of the olfactory nerve which splay out across the dorsal surface of the olfactory sac (Fig. 1). Of these branches, three widely separated branches (viz., the most medial, an intermediate, and the most lateral) subserving different localized regions in the mucosa (Mozell, 1964) were dissected free from the surrounding connective tissue.
These branches were lifted onto bipolar platinum stimulating electrodes (250 μm diam). The animal was grounded through a silver-silver chloride wire which contacted a piece of Ringer's-soaked cotton placed on the bone just posterior to the exposed olfactory bulbs. Electrical stimulation was obtained with a Grass S48 constant voltage stimulator equipped with a Grass stimulus isolation unit (SIU-5) (both from Grass Instrument Co., Quincy, Mass.). Metal-filled micropipets (Gesteland et al., 1959), having tip diameters of less than 5 μm, were used to record single unit activity in the olfactory bulb. This microelectrode was capacitor coupled to a Grass P16 amplifier and the amplified signals were led to both a Tektronix 532 oscilloscope (Tektronix, Inc., Beaverton, Ore.) and a Grass AM-5 audio monitor. Photographic records were taken of the scope display with a Grass C-4 Kymograph camera.

**Procedures**

Electrode penetrations were made within a band of coordinate positions which was found to optimize the possibility of encountering units in the mitral cell layer of the olfactory bulb (see section on Electrode Placement). Once a single bulbar unit was identified and its exact coordinate position noted, its responsiveness to the electrical stimulation of each of the three olfactory nerve branches was tested. For each bulbar unit each of the three nerve branches was stimulated with a series of test pulses 0.1 ms in duration and ranging in voltage from 10 to 60 V. (In preliminary experiments it was found that if a unit did not respond at 60 V, it would not respond at higher voltages.) The inset of Fig. 1 represents a response typical of those recorded from these bulbar units after stimulation of an olfactory nerve branch. The response consists of a single driven spike superimposed on an evoked field potential. In order to emphasize the spike itself, signals were routinely filtered to selectively attenuate the field potentials. The analysis of the data to be presented is based upon the presence or absence of the driven spike only.

In Fig. 1 the interval between stimulus onset and the spike response was 110 ms. Since the distance between the stimulating and recording electrodes was approximately 1.5–2.0 cm, a conduction velocity of 0.14–0.18 m/s was estimated. This conduction velocity is comparable to values reported by Gasser (1956) for olfactory nerve fibers of the pike.

**Control for the Spread of Stimulus Current**

Since these experiments were designed to test the responsiveness of bulbar units to the stimulation of different nerve branches subserving different localized regions of the mucosa, it was important to restrict the spread of current at each of the stimulation sites. If current spread were sufficiently great, it might affect more than one of the test nerve branches and result in a bias against finding units that responded selectively to only one of the nerve branches. To prevent significant spread of stimulus current, several steps were taken. These included the use of a stimulus isolation unit, the use of a very short pulse duration (0.1 ms), and the selection of nerve branches that were widely separated from each other.

In order to test the effectiveness of these precautions, control experiments, which involved testing for bulbar unit responses before and after cutting one of the test nerve branches, were conducted in two different preparations (see Fig. 2 for details). The results of these control experiments demonstrated that if there were any spread of stimulus current, this current was incapable of producing a bulbar unit response via neighboring nerve branches.

**Electrode Placement**

In order to identify the regions of the olfactory bulb having the highest density of mitral cells, the olfactory bulbs of five animals were prepared for histological examination.
Sagittal sections, horizontal sections, and cross sections were all studied, and as can be seen in Fig. 3a, the olfactory bulb of the frog was found to be organized into four histologically distinct layers. As seen from the surface, the mitral cells were found to occupy a more central region of the olfactory bulb (see Fig. 6) falling within the \((x,y)\) coordinate positions \((\pm 8, \pm 4)\).

Electrode penetrations were made within those coordinate positions found to contain the highest density of mitral cells. In five different animals, histology was used to confirm that the electrode had been located within the mitral cell layer. In these five preparations, after recording from a single unit, the tapered shaft of the microelectrode was pinched off at the surface of the bulb and the location of the remaining tip was identified in the histological sections. In all but one of these preparations each electrode tip was clearly located within the mitral cell layer (see Fig. 3b). In the one remaining preparation, even though the electrode tip itself could not be identified, the position of the electrode shaft strongly indicated that it had penetrated into the mitral cell layer.

**RESULTS**

*Nerve Branch Response Profiles for Bulbar Units*

The nerve branch response profile of a unit was characterized from its pattern of responses or lack of responses to the stimulation of each of the three nerve branches. If a unit responded to the stimulation of a given nerve branch at any
of the test voltages (10-60 V), it was considered to have a positive response to that nerve branch.

The results of a typical experiment using the above criteria are illustrated diagrammatically in Fig. 4. The unit studied was located at a coordinate position (+5, +2) which is a relatively lateral position in the olfactory bulb. This unit was characterized as having a “0++” nerve branch response profile, indicating that it did not respond to stimulation of the medial nerve branch but did respond to stimulation of the intermediate and lateral nerve branches. Although in Fig. 4 the responsiveness to only one series of test voltages is shown for each nerve branch, in most experiments (including that illustrated in Fig. 4) the entire stimulus series was repeated at least two times.

**Figure 2.** Control experiment for the spread of stimulus current. Figure on the left illustrates the responsiveness of a bulbar unit to the stimulation of two neighboring nerve branches in the olfactory mucosa. Once the responsiveness of the unit (frames 1 and 2) to stimulation of the two adjacent nerve branch sites (A and B) was confirmed, one of the nerve branches was carefully severed at a point between the stimulation site (B) on the distal portion of the nerve and the portion of the nerve more proximal to the olfactory bulb (see figure on right). After cutting the nerve, stimulation to the distal nerve stump (site B) was found to no longer elicit a response (frame 4). This indicated that there was no spread of stimulus current from site B sufficient to give a response in neighboring nerve branches. The response to subsequent stimulation of the uncut branch (frame 3) served as a control to assure that the bulbar unit had not been lost when severing the nerve branch. The position of the single unit in the olfactory bulb is indicated by the filled circle. Arrows indicate stimulus onset. Each record is 500 ms in duration.

Fig. 5 illustrates the response profiles of three additional units. These three units are all from the same animal and appear from left to right in the order in which they were encountered. The three replications of the stimulus series for each nerve branch shown in Fig. 5 demonstrate that response sequences were quite reproducible.

The first unit (Fig. 5) was located in a more medial region of the bulb (-8, +2) and was responsive to only the medial nerve branch (+00 unit). The second unit located near the center of the bulb (-2, -2) was responsive to each of the three nerve branches (+ ++ unit). The third unit, located in a medial region of the
Figure 3. A, Sagittal section of the olfactory bulb illustrating the principal cell layers. Hematoxylin and eosin stain. Horizontal bar, 650 μm. B, Sagittal section of the olfactory bulb showing the electrode tip located in the mitral cell layer. Cresyl violet stain. Horizontal bar, 200 μm. N, nerve layer; Gl, glomerular layer; M, mitral cell layer; Gr, granular cell layer.
bulb (−4, −3), was responsive to both the medial and intermediate but not the lateral nerve branch (+ +0 unit).

In addition to the nerve branch response profiles illustrated in Figs. 4 and 5, three other response profiles were observed, giving a total of seven different response profiles. To summarize, they were: (a) units that were driven by stimulation of the medial nerve branch but not by the intermediate or the lateral nerve branches (+00 units); (b) units that were driven by the medial and intermediate nerve branches but not by the lateral nerve branch (+ +0 units); (c) units that were driven by the medial, intermediate, and lateral nerve branches (+ + + units); (d) units that were driven by the lateral but not the intermediate or the medial nerve branches (00+ units); (e) units that were driven by the lateral and intermediate nerve branches but not the medial nerve branch (0+ + units); (f) units that were driven by the intermediate nerve branch but not the medial or lateral nerve branches (0+0 units); (g) units not driven by any of the three nerve branches (000 units). One additional type, +0+, was theoretically possible, but was not found in the 93 units studied.

It is conceivable that differences in electrode impedance or differences in the contact of the electrodes with their respective nerve branches could account for the various response profiles observed. However, both the techniques employed and the results observed make this possibility appear highly unlikely. First, the 250-μm platinum wire hook electrodes used for stimulation had relatively low impedance and provided a relatively large contact area with the nerve branches. Second, a wide range of voltages was used to stimulate each nerve branch and if a bulbar unit responded to any of these voltages, that nerve branch was, without further qualification, simply classified as having an excitatory effect. Finally, as exemplified in Fig. 5, units with very different response profiles were quite often

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**Figure 4.** Diagrammatic representation of a typical experiment. Figure illustrates the left olfactory bulb with coordinates indicating the position of the bulbar unit (Θ). A, B, and C represent the most medial, the intermediate, and the most lateral olfactory nerve branches respectively, as they are lifted onto stimulating hook electrodes. Table lists the responses to stimulation of the respective nerve branches at the voltages listed. This unit has a 0+ + nerve branch response profile.
observed even when, in the same preparation, the position of the stimulating electrodes remained unaltered. Indeed, units with different response profiles were found in 71% of the preparations in which more than one unit was tested and in which the electrode positions remained stationary. Such results do not seem commensurate with the suggestion that either electrode impedance or the electrode contact per se can underlie the response profiles observed for different bulbar units.

![Diagram of olfactory bulb and nerve branch stimulation](image)

**Figure 5.** Responses of three bulbar units illustrating three different nerve branch response profiles. Each unit is from a different bulbar position in the same preparation. Lower tables illustrate responses to nerve branch stimulation. Responses to three different replications of each stimulus voltage for each nerve branch are given. Above the diagram of each olfactory bulb is given the nerve branch response profile for the respective unit. The meaning of the different symbols used to depict the coordinate positions of the units will be discussed in conjunction with Fig. 6.

**Topographical Distribution of Units with Different Nerve Branch Response Profiles**

Fig. 6 shows the results of 51 single units sampled from different locations across the olfactory bulb. The olfactory bulb was considered to be divided into three general regions: a medial region, an intermediate region, and a lateral region. 17 units from each of these three regions (51 in all) were classified according to their nerve branch response profiles.

Units which did not respond to stimulation to any of the three nerve branches (000, open circles) were distributed nonspecifically across the different regions of the olfactory bulb. Units responsive to each of the three nerve branches (+++, filled circles) were similarly distributed nonspecifically.

Of particular interest were those units which from their response profiles appear to receive their excitatory inputs from specific regions of the olfactory mucosa. For example, the response profiles of some units (+++ and +00 units)
indicated a bias to inputs from the more medial aspect of the mucosa. To illustrate this medial bias in Fig. 6 these units are designated by circles shaded on the left (i.e. shaded on the medial side). As can be seen in Fig. 6, all units having a medial bias were located only in the most medial region of the olfactory bulb. No units of this type were found in the intermediate or lateral regions of the bulb.

Other units were found to have a bias to inputs from the more lateral aspect of the mucosa and were therefore designated in Fig. 6 by circles shaded on the
right (lateral side). These laterally biased units were found only in the lateral region of the bulb.

One unit was found to have a selective input from the intermediate nerve branch alone. This unit was located in an intermediate region of the olfactory bulb and is designated by a starred circle with a bar down the center.

Columns A–E of Table I summarize the data shown in Fig. 6. For each of the three regions of the bulb is given the actual number of cells within each response profile category. This number is also given as a percentage of the 17 cells sampled in each of the three bulbar regions. Cells having a medial bias (+00 and ++0 units) represent 35% of the cells sampled from the medial bulb. Laterally biased cells (00+ and 0++) made up 47% of those sampled from the lateral bulb region. (If one were to eliminate from the analysis the 000 cells that did not respond at all to any of the three nerve branches, the percentage of cells showing a medial or lateral bias would, of course, be even greater.)

**Increased Sample Size**

The results of the experiments given in Table I (A–E) show that a considerable proportion of the cells in different regions of the olfactory bulb have a bias with respect to inputs from different regions of the olfactory mucosa. Although a total of 51 units were sampled from across the olfactory bulb, the number of cells sampled in any one region was relatively small ($n = 17$) and since there was a possibility of seven different response profiles that could possibly be partitioned among these 17 units, estimates of the percentages of each type of response profile could be considered first approximations only. Furthermore, the failure to observe cells with particular types of response profiles in a given region of the bulb (for example, a laterally biased unit in the medial bulb) may have also been the result of this small sample size. To most efficiently increase the sample size in order to determine whether units with a particular mucosal regional bias are restricted to a particular bulbar region, an additional 42 units were sampled from the lateral region of the bulb only. This increased the total number of cells

|              | Medial bias | Intermediate bias | Lateral bias | No bias | No response |
|--------------|-------------|-------------------|--------------|---------|-------------|
| A Response profile | Medial | Intermediate | Lateral | F Lateral |
| n=17 % | n=17 % | n=17 % | n=59 % |
| Medial bias | +00 | 29 | 0 | 0 | 0 | 0 |
| | ++0 | 6 | 0 | 0 | 0 | 0 |
| Intermediate bias | 0+0 | 0 | 0 | 1 | 6 | 0 | 0 |
| Lateral bias | 00+ | 0 | 0 | 0 | 0 | 3 | 18 | 11 | 19 |
| | 0++ | 0 | 0 | 0 | 0 | 5 | 29 | 13 | 22 |
| No bias | +++ | 5 | 29 | 8 | 47 | 4 | 24 | 22 | 37 |
| No response | 000 | 6 | 35 | 8 | 47 | 5 | 29 | 13 | 22 |
sampled from this region to 59 units. Fig. 7 shows the locations in the olfactory bulb of all 59 of these units.

Column F of Table I summarizes the results from the 59 units which can be compared to the data for the original 17 unit sample given in column E. Even with the increase in sample size, the relative percentages of the different cell types did not change appreciably. Furthermore, those response profiles (+00, + +0, 0+0) that were not present in the small lateral cell sample did not appear when the number of cells sampled was increased threefold.

**DISCUSSION**

**Topographical Projections**

Fig. 6 illustrates the existence of a topographical organization of neural projections from different regions of the receptor sheet onto different regions of the olfactory bulb. Cells in the medial region of the olfactory bulb are frequently biased to inputs from the medial region of the mucosa and cells in the lateral region of the bulb are frequently biased to inputs from the lateral regions of the mucosa. Furthermore, as seen in Table I, no instances of crossover in these projections were found. That is, there were no medially biased cells (+00, + +0) in the lateral region of the bulb and no laterally biased cells (00+, 0+ +) in the medial region of the bulb. These findings give functional support to the studies of Le Gros Clark (1951) and those of Land (1973) which provided histological evidence for topographical projections. Furthermore, these findings reveal an organization of projections which is readily compatible with what might be expected if olfactory discrimination were based upon a spatiotemporal analysis (Adrian, 1954).

**Spatiotemporal Analysis of Odorants**

As already indicated, there are at least two different but not mutually exclusive hypotheses for the mechanisms generating spatial and temporal patterns: (a)
clusters (or aggregates) of selectively sensitive receptors, and (b) differences in the distribution of odorant molecules across the mucosa. In either case, the analysis made at the mucosal level should be preserved for further processing in the more central levels of the olfactory system by a topographical projection of the mucosa onto the olfactory bulb.

Consider the case in which the olfactory receptor sheet consists of clusters of receptor cells having different degrees of sensitivity to different odorants. Consider further that clusters of cells with similar sensitivities may be spaced across the mucosa in different sequential locations. Each odorant would then give rise to a unique spatial and temporal pattern of activity as its molecules, moving along the mucosa, interact with its particular sequence of sensitive clusters. If such selectively sensitive clusters are present in the mucosa, the spatiotemporal pattern that they would establish could be preserved for the central nervous system by the presence of topographical projections such as those observed in this study.

However, it should be noted that these clusters, if they do exist, might be arranged in a finer mosaic than could be sampled by the size of the nerve bundles stimulated in the present study. Therefore, to further investigate these putative clusters, the techniques employed might have to be refined to allow for the electrical stimulation of nerve branches more peripherally where they are subdivided into even smaller fascicles. Consequently, in the strong support given by this study to the general concept of a topographical projection of mucosal activity onto the bulb, no suggestion is made to preclude the possibility that an even finer point-to-point projection might exist than that reported here.

In addition to clusters of selectively sensitive receptors, spatiotemporal differentiation might be based upon the different migration patterns of various odorants across the mucosal sheet. That molecules of different odorants move across the mucosa in different space-time distribution patterns has been strongly indicated by both electrophysiological and gas chromatographic studies (Mozell, 1966, 1970; Mozell and Jagodowicz, 1973). In addition, recent isotope studies have shown a steep concentration gradient from the external naris to the internal naris after a “sniff” of tritiated butanol molecules (Hornung et al., 1975). Such differential distributions of molecules across the mucosa could be reflected in the activity of the olfactory bulb by means of a topographical projection of the mucosa onto the bulb.

Consider for an example two chemicals, carvone and octane, known to produce different activity patterns across the olfactory mucosa (Mozell, 1970). Carvone gives a response more limited to the medial region of the mucosa than does octane. The latter gives responses of about equal strength in both the lateral and the medial regions. Conceivably, then, both chemicals might excite those cells in the medial bulb which have a bias to the medial mucosa. However, those cells in the lateral bulb having a bias to the lateral mucosa might respond more strongly to octane than to carvone. Thus, in terms of the present results, octane might excite all those cells in the bulb having the following response profiles: 00+, 0+++, 0+0, ++0, +00, +++. Carvone, on the other hand, would excite most those bulb cells with the following response profiles: +00, ++0, +++. Therefore, these two chemicals would initially establish two different
activity patterns across the mucosa. A reflection of these patterns could then be preserved across the bulb by the topographical projection functionally demonstrated in the present study.

**Inhibition**

Although a "0" in the response profile indicated the absence of an excitatory influence of a particular nerve branch on a bulbar unit, it did not necessarily indicate that there was no influence at all from that nerve branch. It is possible that the bulbar unit may have been *inhibited* rather than simply not excited. If this were the case, a 0 in a unit's response profile could represent an inhibitory region in its receptive field. The experimental design was not intended to distinguish between these two alternatives and indeed the low rate of spontaneous activity (circa 0.4 spikes/s) for the bulbar units would make such observations particularly tenuous. At any rate, the possibility of inhibitory regions in the receptive field of a bulbar cell is important since in other sensory systems (Mountcastle, 1957; Hubel and Wiesel, 1968; Hartline et al., 1956; Rose et al., 1959) lateral inhibition in particular has been found to be fundamental to the sharpening of stimulus differences. Perhaps a similar mechanism occurs in olfaction.

**Receptive Field Size**

The response profiles of a bulbar unit (Figs. 6 and 7) can be taken as an index of the size of its excitatory receptive field across the roof of the olfactory sac. Some units (viz., +00, 0+0, 00+) appear to get their excitatory inputs from relatively small regions of the dorsal olfactory mucosa. Other cells (++0 and 0+++) have wider projections and still other cells (++++) did not appear to have any localization of inputs from the dorsal mucosa. Thus it appears that the overall population of second order cells in the olfactory bulb is made up of different cell types each having different degrees of spatial specificity from the receptor sheet. However, it should be noted that since this study was confined to nerve branches subserving the dorsal receptor sheet, the size of the receptive fields of some bulbar units may have been somewhat underestimated.

Recognizing the possibility of species variations in the precision of the projection onto the bulb of particular epithelial regions, it might still be pointed out that the differences in receptive field sizes reported here are not inconsistent with the results of the earlier histological work cited above. This histological work also showed mucosal projections onto the rabbit bulb which varied widely along a continuum running from "precise" to "diffuse." In addition, the present findings do not seem inconsistent with those of Freeman (1974). His observation that the stimulation of olfactory nerve axons produces an evoked potential encompassing much of the bulb surface seems compatible with the present observation that each part of the bulb has many units which receive their inputs from wide regions of the mucosa. Perhaps the spatial shift in the epicenters of the evoked potentials which Freeman noted as he changed the position of his stimulating electrode reflects the change that this maneuver would engender in the pool of those bulbar units (identified in the present study) which receive their excitation from more localized receptive fields.
Implications

Other sensory systems have been shown to project the spatial organization of their peripheral receptor sheet onto more central levels of the system. In some cases this projection coupled with lateral inhibitory interactions is critical to the analysis of the stimulus spectrum which begins in the periphery as a spatial distribution across a receptor sheet. This study has functionally demonstrated a topographic projection of the olfactory receptor sheet onto its second order neurons in the olfactory bulb. It may be that, as in other sensory systems, a spatial analysis of the stimulus at the receptor level is an essential feature in the processing of olfactory information.

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