

## Research Reports

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### CORTICAL CONNECTIONS OF THE OCCIPITAL LOBE IN THE RHESUS MONKEY: INTERCONNECTIONS BETWEEN AREAS 17, 18, 19 AND THE SUPERIOR TEMPORAL SULCUS\*

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(Accepted October 16th, 1980)

*Key words:* striate cortex — prestriate cortex — superior temporal sulcus — visual areas — occipital lobe

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#### SUMMARY

Using both anterograde and retrograde tracing techniques, the present report investigates the cortical connections of the lateral, medial and ventral portions of areas 17 and 18 in the rhesus monkey. All parts of area 17 are found to send topographically organized connections to a strip of prestriate cortex which closely corresponds to area OB of Bonin and Bailey or area 18 of Vogt and Vogt. Striate-recipient area 18, in turn, is topographically connected with an anterior prestriate zone, whose borders coincide with those of area OA or 19. These efferents are topographically organized, with connections from the medial surface of area 18 directed to lateral parts of area 19. In addition, certain parts of area 18, in the annectent gyrus and the inferior occipital sulcus, send 'crossed', dorsoventral connections to ventral and dorsal parts of area 19, respectively. Both areas 17 and 18 project in a topographic fashion to a distinct region in the caudal part of the superior temporal sulcus. Topographically organized reciprocal connections are also found from area 18 to 17, from area 19 to 18, and from the superior temporal sulcus to both areas 17 and 18.

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#### INTRODUCTION

Prestriate cortex in the rhesus monkey is composed of several areas, including a

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\* A preliminary report of these findings has been presented elsewhere<sup>21,22</sup>.  
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posterior striate recipient zone (V2 and V3), an anterior non-striate recipient zone, and a small additional striate recipient area in the caudal part of the superior temporal sulcus<sup>32,41,43-47</sup>. The precise boundaries of these prestriate subdivisions have recently been explored both by electrophysiological mapping<sup>15,32,45</sup> and anatomical investigations of callosal or corticocortical connections<sup>6,18,31,37,39,41</sup>. Except for the superior temporal sulcus visual area, however, the boundaries and topographic organization of prestriate cortex have been only partially delineated. Anatomical studies of cortical connections have primarily concentrated on connections from the lateral surface of the occipital lobe, so that comparatively little information is available for large portions of visual cortex located more medially and ventrally. Thus, the full extent of striate-recipient cortex is not known, and the topographic continuity of connections from the lateral and medial parts of area 17 is not well established. There is also the possibility, as recently reported by Zeki<sup>47</sup>, that the connections of the medial surface may not be precisely analogous to those on the lateral surface. Medial striate cortex, representing the peripheral visual field, appears to send projections not only to two prestriate areas (as does lateral striate cortex) but also to a third visual area (V3A).

Anterior prestriate cortex, area OA or 19, is known to receive connections from area 18 (including areas V2 and V3; see below — Nomenclature), but again available studies have dealt mainly with portions of area 18 located on the lateral surface of the hemisphere<sup>6,13,41</sup>. The full extent of '18-recipient' cortex has not been determined, nor is the topographic organization of these connections clear.

Both areas 17 and 18 send projections to the superior temporal sulcus<sup>22,44</sup>. The connections from area 17 are organized in a precise topographic fashion<sup>18,30,37</sup>. It is not presently known, however, whether the connections from area 18 to the superior temporal sulcus are also topographically organized, nor whether these are directed exclusively to the striate-recipient zone in the sulcus. With these issues in mind, the present investigations were undertaken to focus on the efferent cortical connections of medial and ventral portions of both areas 17 and 18, in comparison with the connections from the lateral surface.

## MATERIALS AND METHODS

Eighteen monkeys were injected with tritiated amino acids (<sup>3</sup>H]proline and <sup>3</sup>H]leucine) in different parts of the occipital lobe (areas 17, 18 and 19). In each case, 2–4 injections of isotope, at final concentrations of 25–80  $\mu\text{Ci}/\mu\text{l}$ , were made (0.6  $\mu\text{l}$  per injection). After a survival time of two days (two animals: cases 4 and 10) or 6–10 days (the remaining 16 animals), the monkeys were deeply anesthetized and perfused intracardially with either 10% formalin or with standard Karnovsky fixative, containing 1% paraformaldehyde and 1.25% glutaraldehyde<sup>10</sup>. Tissue was then processed for autoradiography according to the techniques described by Cowan et al.<sup>5</sup>, and exposed to photographic emulsion for at least 3 months.

Twelve other animals received injections of Sigma VI horseradish peroxidase (HRP) in different parts of areas 17, 18 or 19. One or two injections of HRP (20% aqueous solution; 0.2–0.6  $\mu\text{l}$  per site) were made in each case. Following a 2-day

survival period, these animals were perfused according to the protocol described by Rosene and Mesulam<sup>24</sup>. After storage in sucrose buffer for 12–24 h at 0 °C, the brains were cut into 40  $\mu$ m sections on a freezing microtome and prepared according to either the benzidine dihydrochloride or the tetramethyl benzidine incubation procedures<sup>16, 17</sup>. The distribution of terminal labeling and HRP-positive neurons was charted with the aid of an x–y plotter.

In addition, several unoperated hemispheres, stained with cresyl violet, were used to analyze the cytoarchitectonic characteristics of various subdivisions of the occipital lobe. Injections in striate cortex were made in representative visuotopic subdivisions, as described by Daniel and Whitteridge<sup>7</sup>. Within prestriate cortex, injections were mainly restricted to the architectonic zones delineated by Bonin and Bailey<sup>2</sup>. In some cases, the injected isotope or HRP nevertheless spread beyond these limits. The interpretation of results in such cases was based on a comparison with other injections which were well confined within a single architectonic field.

#### *Architectonic analysis and nomenclature*

The connections from striate cortex outline two broad subdivisions within prestriate cortex, namely, the posterior or striate-recipient region and the anterior, non-striate-recipient region. According to our observations, these two subdivisions closely correspond to the architectonic areas OB and OA<sup>2</sup>, respectively, or to areas 18 and 19 of Vogt and Vogt<sup>28</sup>. According to both these parcellations, area 18 (OB) on the lateral surface is limited to the posterior bank of the lunate sulcus and the posterior third of the inferior occipital sulcus (IOS), while area 19 (OA) occupies the anterior bank of the lunate sulcus, along with the entire preoccipital gyrus, and the anterior portion of the IOS. (This is a smaller territory than the area 19 outlined by Brodmann<sup>4</sup>.)

In the present study, areas 18 and 19 were provisionally identified by reference to the boundaries of Bonin and Bailey. Area 18 was identified by its characteristically dense third layer. The large pyramidal cells of this layer are scattered deep in sublamina IIIc and abut directly onto layer IV. The fourth layer, moreover, is thick and contrasts with a light layer V. The sixth layer in area 18 is dense and 'clumpy', and usually sharply set off from the white matter. In contrast, area 19 exhibits a much lighter third layer. The pyramidal cells in layer III are, on the whole, smaller in size than those in area 18, and are arranged in more orderly, linear groupings. A small space is usually maintained between the pyramidal cells in layer IIIc and the underlying fourth layer. In area 19 layer Va is darker when compared with the same layer in area 18; layer VI is broader, but less dense; and the sixth layer typically blends smoothly with the white matter. Within both areas 18 and 19, there is some evidence for further subdivisions. For example, within area 19, one ventral subdivision, area 19a<sup>28</sup> or TEO<sup>3</sup>, has been widely recognized.

## RESULTS

In the first group of experiments, cortical connections from area 17 are

investigated by isotope injections in the lateral and medial surfaces of the occipital lobe (cases 1–5) and by HRP injections in area 18 (cases 6–8). These HRP injection sites were placed to coincide with the specific projection zones in area 18 that were revealed by the isotope injections in area 17. In the second group of experiments, cortical connections from area 18 are similarly investigated, using both isotope injections in area 18 (cases 9–14) and HRP injections in area 19 (cases 15–20). Finally, reciprocal connections from area 18 to area 17, and from area 19 to area 18 are also investigated by both anterograde (cases 10, 21, 22; 25–29) and retrograde (23, 24, 30) techniques.

### *Efferent connections of area 17*

#### *1. Isotope injections*

Two animals received injections in striate cortex located on the lateral surface. In

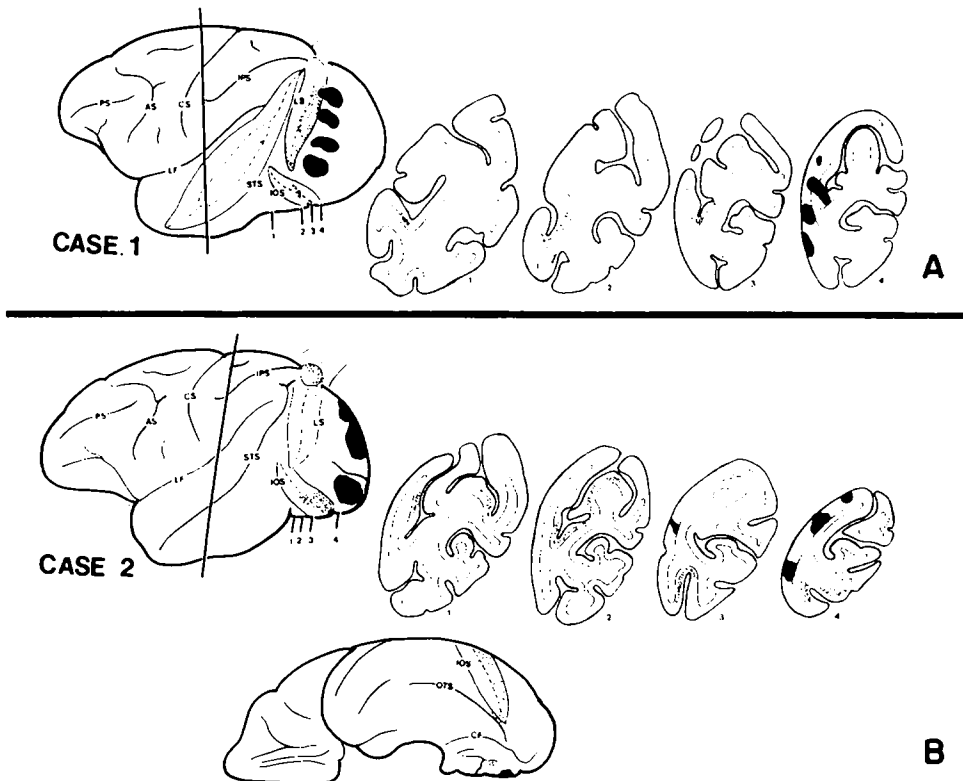


Fig. 1. Diagrammatic representation of the distribution of silver grains (shown as dots) after isotope injections (shown in solid black) in the rostral (case 1) and caudal (case 2) parts of the occipital cortex. In these and subsequent cases, sulci containing label are shown opened, with the depth of the sulcus represented along the dashed lines. Coronal sections are taken from the correspondingly numbered levels on the brain diagram. Grains occurring in the immediate vicinity of injection sites are not shown. Abbreviations: AS, arcuate sulcus; CF, calcarine fissure; Cing. S., cingulate sulcus; CS, central sulcus; IOS, inferior occipital sulcus; IPS, intraparietal sulcus; LF, lateral fissure; LS, lunate sulcus; OTS, occipital-temporal sulcus; POM, parieto-occipital-medialis sulcus; PS, principal sulcus; STS, superior temporal sulcus.

case 1 (Fig. 1A), 4 small isotope injections were made in the rostral portion of area 17, parallel to the lunate sulcus. The most dorsal injection encroached somewhat upon area 18 cortex in the adjoining lunate operculum. Case 2 (Fig. 1B) had injections placed around the occipital pole.

In both of these cases, terminal label was found at two sites within area 18: in the lunate sulcus (LS) and in the inferior occipital sulcus (IOS). The injection in case 1 resulted in 3 distinct patches of grains *within the LS*, mainly in its posterior bank and depth. More ventrally, silver grains extended into the anterior bank of the LS as well. The posteriorly placed injections in striate cortex (case 2), however, produced label primarily in the annectent gyrus, with only sparse grains in the dorsal part of the LS. As for the IOS, terminal label in case 1 occurred only in the anterior part of the sulcus; but in case 2, with more posterior injections, was again more caudally located. Finally, in case 1, a third focus was also noted, situated in the ventral portion of the preoccipital gyrus (area 19). Comparisons with other cases (see below) having injections in area 18-type cortex, suggests that this was caused by spread of isotope into the lunate operculum.

In a third case (not illustrated), the injection was aimed at the dorsomedial portion of striate cortex, along the parieto-occipital medialis sulcus (POMS). Here, the main focus of silver grains in area 18 was found in the annectent gyrus, but more medially than in case 2. No label was detected ventrally in the IOS in this case.

In the next two experiments, injections were placed in medial parts of striate cortex. In case 4 (Fig. 2A), isotope was injected within the depth of the calcarine fissure (CF). In this case, the greatest number of grains occurred just ventral to the CF, extending to the collateral sulcus (area 18). Two smaller foci in area 18 were located dorsally in the medial part of the annectent gyrus, and on the interhemispheric surface near the POMS. These may be attributed to spread of isotope to the upper calcarine ramus.

A second animal, case 5, had an injection along both lips of the CF (see Fig. 4B). In the ventral lip, the injection was confined strictly to striate cortex, while the dorsal component of the injection included area 18-type cortex. Just as in case 4, with an injection in the depth of the CF, a large quantity of silver grains appeared in the ventral part of area 18, within the occipito-temporal sulcus. This focus, however, was situated posterior to the projection zone seen in case 4. In addition, case 5 had some label dorsally in area 19. A comparison with the 3 previous cases, where the injections were confined mainly to area 17, suggests that these dorsally situated terminations may be attributed to the injection of area 18-type cortex in the upper lip of the CF.

In all of the above cases, terminal label was also observed in an architectonically distinct region, area OAa<sup>26</sup>, in the posterior part of the superior temporal sulcus. Within that region, silver grains were distributed in a distinct topographic manner. Thus, injections of lateral striate cortex resulted in grain in the lower bank and depth of the sulcus (cases 1 and 2), while injections of medial striate cortex gave rise to grains in the depth of the sulcus, near the junction with its upper bank (cases 3, 4 and 5). The label resulting from medial striate injections occupied a more anterior position within the sulcus.

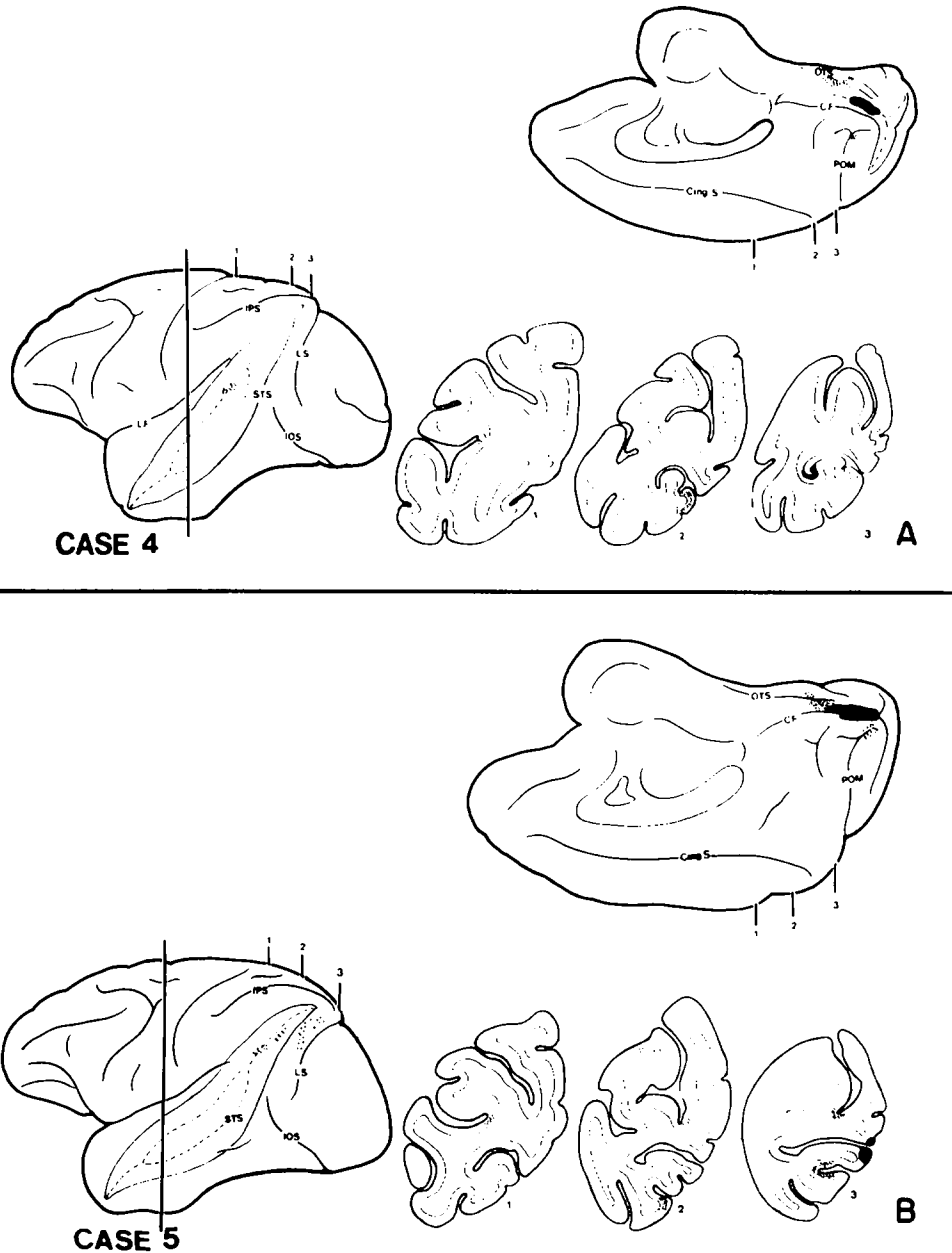


Fig. 2. Diagrammatic representation of the distribution of grains following isotope injections. A: within the depth of the calcarine fissure; and B: along the margins of the calcarine fissure.

2. HRP injections

As shown in Fig. 3, three animals were prepared with HRP injections in different parts of area 18. Injections were designed to involve striate projection zones in area 18, as these were outlined from the above anterograde experiments. In case 6, a small

HRP injection was confined principally to a sector of area 18 in the posterior bank of the lunate sulcus, while in case 7 the injection involved the annectent gyrus. The injection in a third animal (case 8) was located ventrally in the inferior occipital gyrus. In these last two injections, HRP also spread to adjacent portions of area 19.

All of these injections gave rise to HRP-positive neurons in striate cortex. As depicted in Fig. 3, the precise location of these neurons in each instance conformed well to the pattern initially determined using the anterograde method. Thus, an injection of HRP in the caudal bank of the lunate sulcus (case 6) gave rise to a small patch of labeled neurons in area 17 within the adjacent part of the dorsal occipital convexity (cf. case 1, Fig. 1A). After an injection in the annectent gyrus (case 7), labeled neurons appeared in dorsomedial striate cortex, distinctly posterior to those in the previous case (cf. case 2, Fig. 1B). Finally, an injection in ventral area 18 (case 8) produced HRP-positive neurons in area 17 in the lower ramus of the calcarine fissure (cf. case 5, Fig. 2B).

### *Efferent connections of area 18*

#### *1. Isotope injections*

In case 9 (Fig. 4A) isotope was injected in area 18 in the posterior bank of the lunate sulcus. There was also some spread of isotope into area 17 in the adjoining

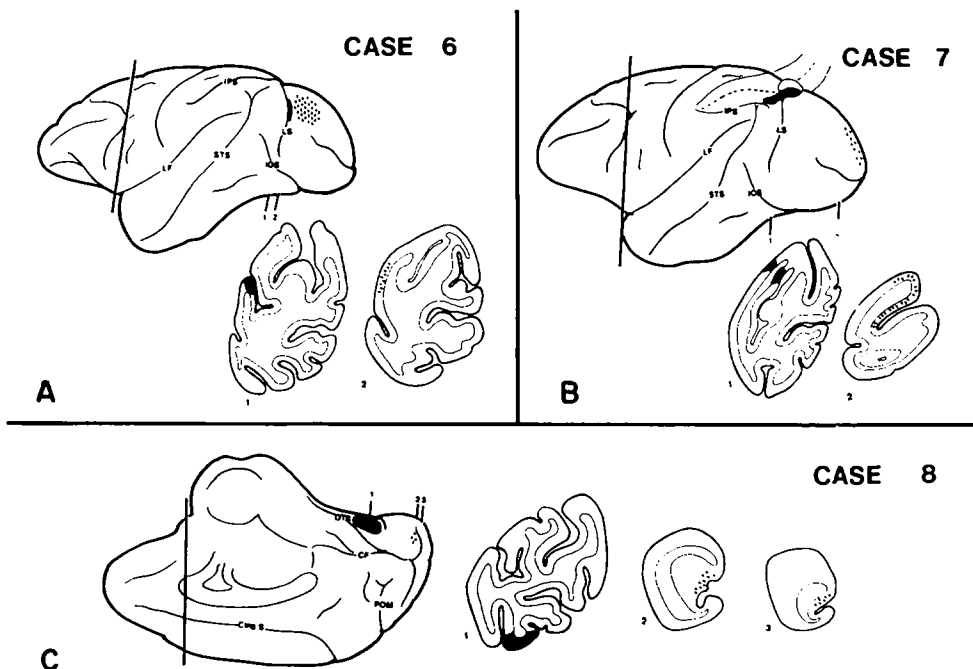


Fig. 3. Diagrammatic representation depicting HRP-positive neurons (shown as solid triangles) in area 17 after HRP injections (shown in black) in different parts of area 18, A: in the caudal bank of the lunate sulcus; B: in the annectent gyrus; and C: in the inferior occipital gyrus. Filled neurons in other cortical regions are not illustrated.

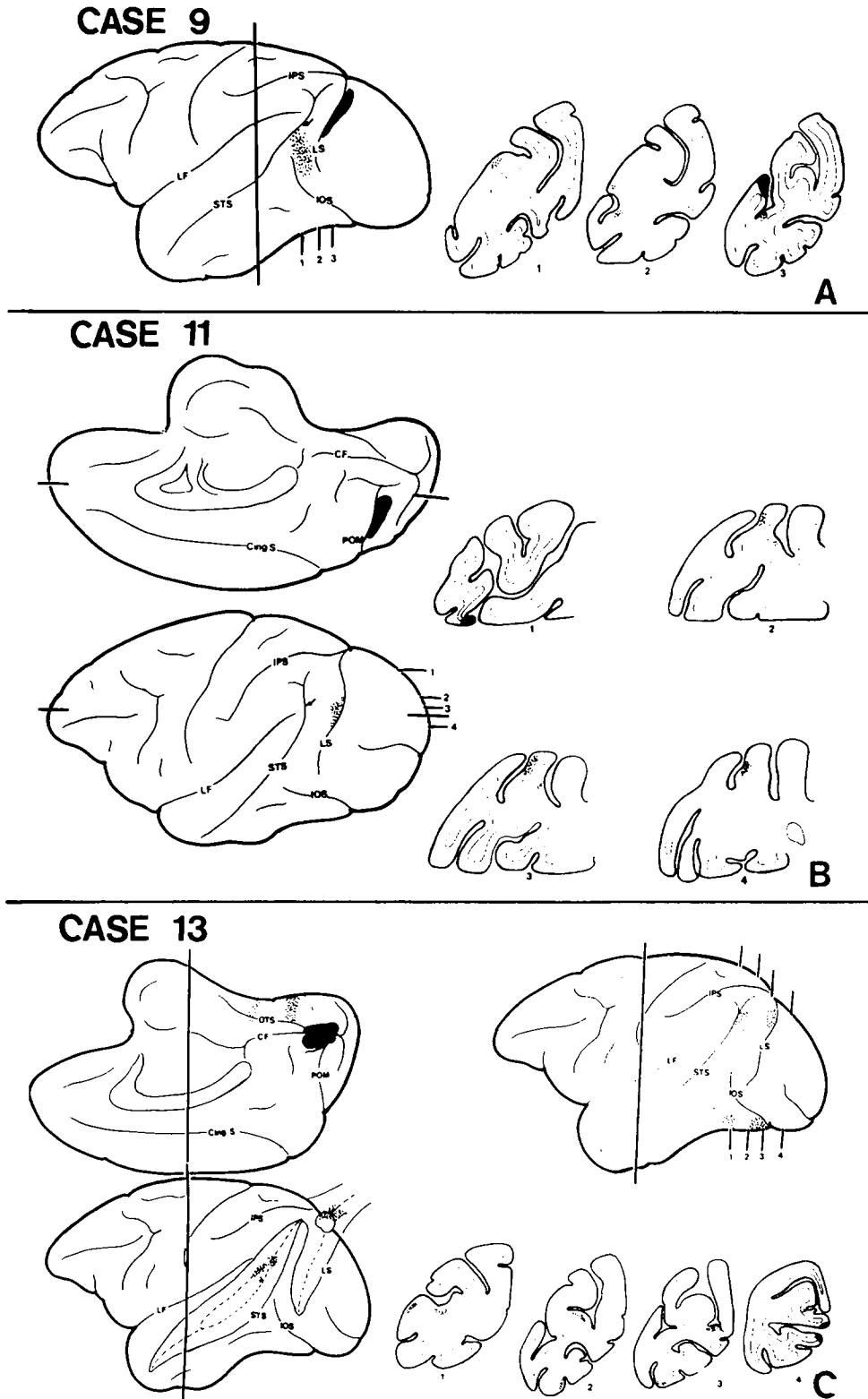


Fig. 4. Diagrammatic representation of the distribution of silver grains after isotope injections in different parts of area 18 in A: the posterior bank of the lunate sulcus; B: the caudal bank of the POMS; and C: the dorsal and ventral lips of the calcarine fissure (with some involvement of POMS and OTS).



occipital operculum. In this case, terminal labeling was observed mainly in the ventral portion of the preoccipital gyrus, remaining within the confines of architectonically defined area 19. In two other animals (cases 10 and 11) injections were placed in more dorsomedial sectors of area 18. In case 10 (Fig. 6A), the injection involved striate-recipient cortex in the caudal and midportions of the annectent gyrus, while the injection in case 11 (Fig. 4B) was in that part of area 18 which lies along the posterior bank of the POMS on the medial surface. In the latter case, some spread of isotope into adjoining striate cortex occurred. In both cases, the majority of labeling was again situated within area 19 in the preoccipital gyrus. Unlike case 9, however, label was now shifted towards a conspicuously more dorsal portion of the gyrus. Furthermore, case 10, with an injection of the annectent gyrus, also had some label in the lunate sulcus (area 19) and *ventrally* near the inferior occipital sulcus.

Two other cases, monkeys 12 and 13, had injections of isotope on the medial surface, along both lips of the calcarine fissure (CF). The injection in case 12 (not illustrated) involved mainly area 18 dorsal to the CF, and area 17 ventral to the fissure; but in case 13 (Fig. 4C), the injection included both areas 18 and 17 along both banks of the CF. The injection in case 13 also included some of area 18 in the POMS dorsally and OTS ventrally. After both experiments, a considerable amount of terminal label was found in the preoccipital gyrus (area 19). In contrast to the previous cases (9–11), however, this occurred in a distinctly more dorsal location. Silver grains also occurred ventrally in both these cases. In case 12, however, where the ventral part of the injection was limited to area 17, grains were strictly confined to the ventral sector of area 18, within the posterior part of the occipito-temporal sulcus, while in case 13, grain occurred more anteriorly around the occipito-temporal sulcus (area 19).

In one animal (case 14, not illustrated), isotope was injected ventrally into striate-recipient cortex (area 18) within the inferior occipital sulcus (IOS) and adjoining inferior occipital gyrus. The anterior part of this injection extended slightly into area 19. As in the previously described cases, the bulk of terminal label resulting from this ventral injection was found within area 19. In contrast to more dorsally placed injections of area 18 (cases 9–11), however, grains in this case were localized primarily within *ventral* area 19, in the lower bank of the IOS and in the adjoining inferior occipital gyrus. A smaller amount of label was also seen in the *dorsal* part of area 19, within the anterior bank of the lunate sulcus and lower bank of the intra-parietal sulcus.

In all the above cases, silver grains were also consistently observed in area OAa<sup>26</sup>, an architectonically distinct sector of the superior temporal sulcus (STS). The distribution of label demonstrated a definite pattern. Thus, after ventral injections, grains were located in the anterior portion of the STS, while after medial injections, they occurred more posteriorly. An injection of the lunate sulcus produced grains in an intermediate location. The heaviest concentration of label in the STS resulted from injection of the posterior bank of the lunate sulcus (area 18).

## 2. HRP injections

Three animals (cases 15–17) received HRP injections in different dorsoventral

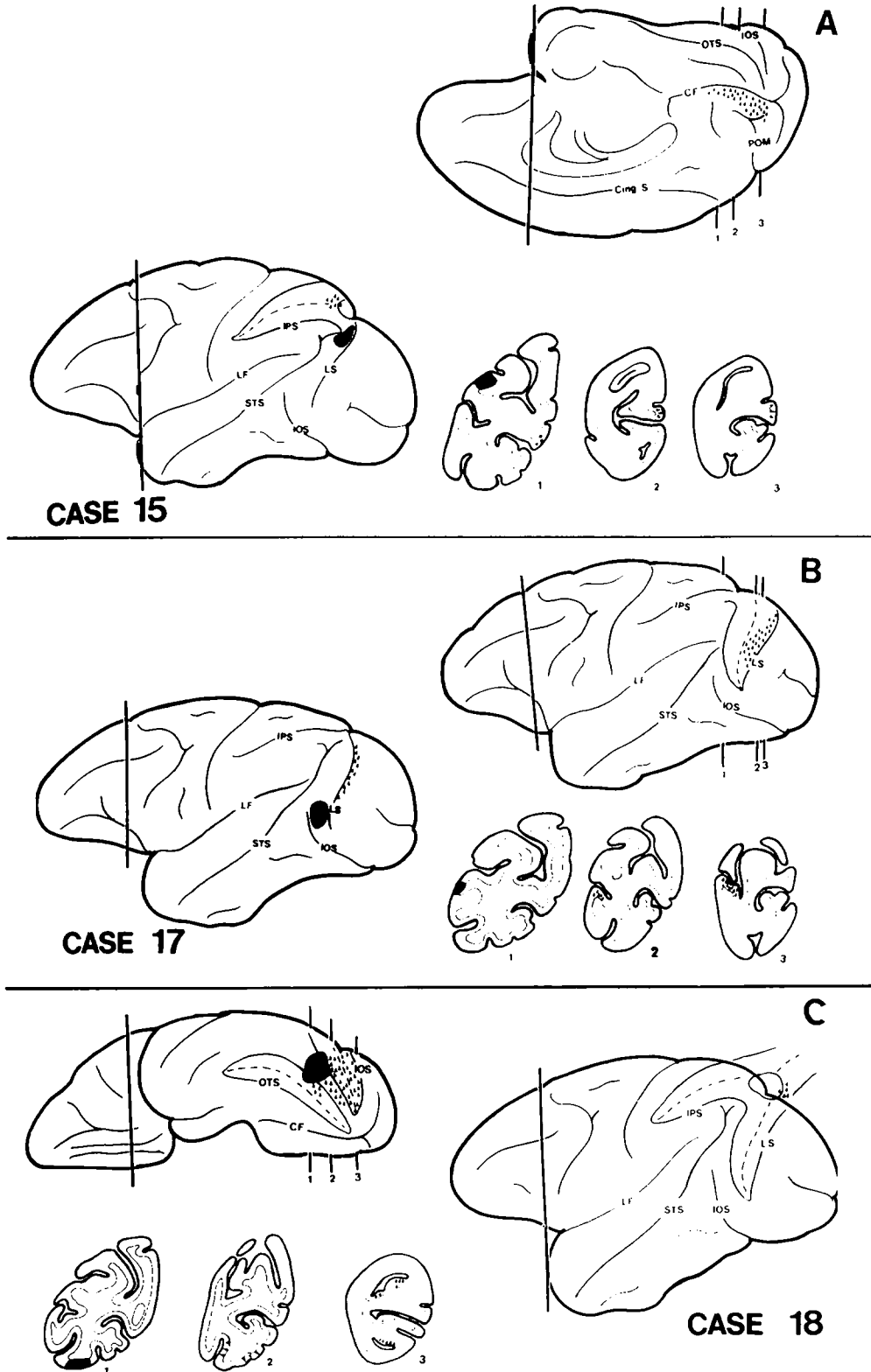


Fig. 5. Diagrammatic representation depicting HRP-positive neurons in area 18 after HRP injections in different parts of area 19 in the dorsal (A) and ventral (B) portions of the precuneus, and ventral to the inferior occipital sulcus (C). Filled neurons in rostral cortical regions are not illustrated.

sites along the preoccipital gyrus. Case 15 (Fig. 5A) had an injection in the dorsal third of the gyrus; case 16 (not illustrated), in its mid-portion; and case 17 (Fig. 5B), in its ventralmost part. These injection sites corresponded to the projection zones in, respectively, cases 13, 10 and 9, as described above. Only HRP-positive neurons in area 18 are described here.

In these 3 cases, the location of HRP-positive neurons in area 18 varied systematically according to the site of the injection in area 19. Thus, after an injection of the ventral preoccipital gyrus (case 17; Fig. 5B), retrogradely filled neurons were found in the posterior bank of the lunate sulcus (compare isotope case 9; Fig. 4A). In contrast, a more dorsal injection, as in case 16, resulted in HRP-positive neurons mainly in the annectent gyrus and on the medial surface (cf. case 10; Fig. 6A). The dorsalmost injection (case 15) produced even more medially displaced labeled neurons, in area 18 cortex above the calcarine fissure (cf. case 13; Fig. 4C). At several coronal levels, filled neurons appeared in 2–3 large clusters, but for the most part no discontinuities or clustering could be detected.

In 3 other experiments (cases 18–20), HRP was injected into area 19 in the ventral portion of the occipital lobe. An injection in the inferior occipital gyrus (case 18; Fig. 5C) resulted in positive neurons within the posterior part of the inferior occipital sulcus and the adjacent gyrus (area 18). In two other, anterior cases (cases 19 and 20, not illustrated) filled neurons were again concentrated in the inferior occipital sulcus, occurring primarily in area 18 cortex within its depth and upper bank. Two of these cases with ventral injections (18 and 20) had additional labeled neurons in *dorsal* parts of area 18 (in the occipital operculum: case 18, Fig. 5C). These results therefore confirm the topographic relationship between areas 18 and 19, as well as the existence of connections between dorsal area 18 and ventral area 19, also indicated by the anterograde technique (see case 10; Fig. 6A).

### *Efferent connections from area 18 to area 17*

#### *1. Isotope injections*

In 3 animals, isotope injections were placed in different parts of area 18; namely, in the lateral lip of the inferior occipital sulcus (case 21), the annectent gyrus (case 10), and the upper lip of the calcarine fissure (case 22). In all 3 cases, terminal labeling occurred in area 17, with its position varying according to the site of the injection. Thus, the ventral injection at the upper lip of the inferior occipital sulcus (not illustrated) gave rise to silver grains in adjacent striate cortex in the ventrolateral occipital convexity. By contrast, the dorsal injection of the annectent gyrus (Fig. 6A) produced grains in dorsomedial striate cortex and within the upper ramus of the calcarine fissure. The third injection, at the upper lip of the calcarine fissure (not illustrated), resulted in a focus of terminal label within the upper bank of the calcarine fissure, extending some distance away from the injection, into area 17.

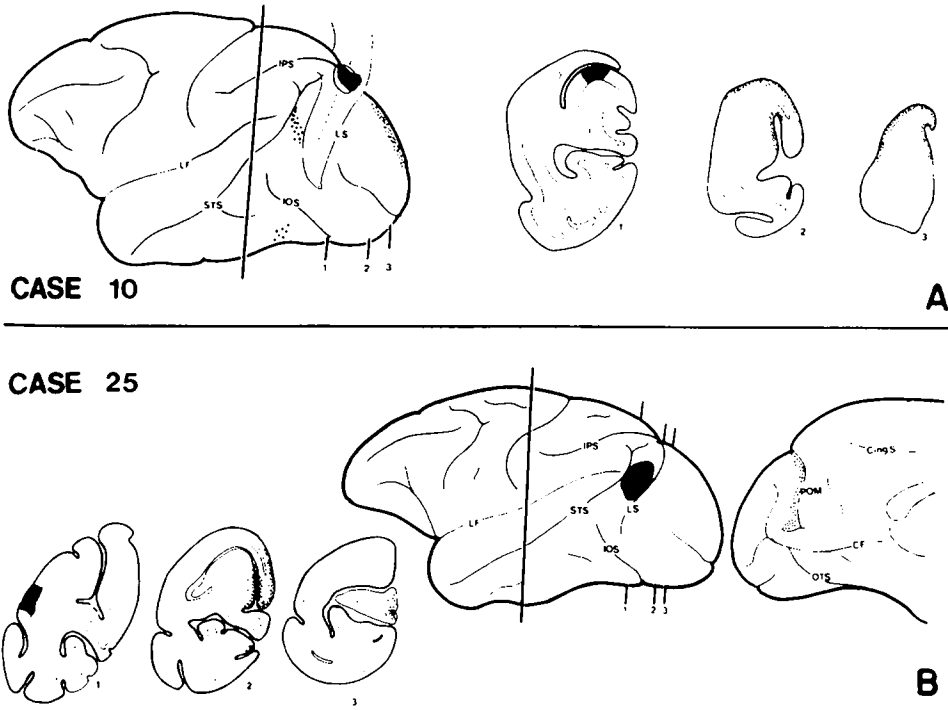


Fig. 6. Diagrammatic representation of A: distribution of silver grains in areas 17 and 19 following an isotope injection in area 18 in the annectent gyrus; and B: grains in area 18 following isotope injections in area 19 in the middle portion of the preoccipital gyrus.

## 2. HRP injections

The topography of parastriate to striate connections was further explored by making several injections of HRP into area 17. In case 23 (not illustrated), a small injection was placed in ventrolateral striate cortex. HRP-positive neurons were visualized in area 18 within the upper bank of the inferior occipital sulcus, in a similar location as the isotope injection site (within area 18) in case 21, described above.

In another experiment (case 24) HRP was injected in the occipital pole and depth of the underlying calcarine fissure (Fig. 7A). In this case labeled neurons were concentrated, in area 18, in the inferior occipital and occipito-temporal sulci, as well as in the intervening inferior occipital gyrus. Aside from these HRP-positive neurons, there were labeled neurons in the superior temporal sulcus and, ventrally, in areas TEO and TF of the inferotemporal region.

### *Efferent connections from area 19 to area 18*

#### 1. Isotope injections

In 5 cases, isotope injections were placed in different parts of area 19; namely, in the middle portion of the preoccipital gyrus (cases 25 and 26), the ventral portion of the gyrus (cases 27 and 28), and in case 29, ventral to the inferior occipital sulcus. In all

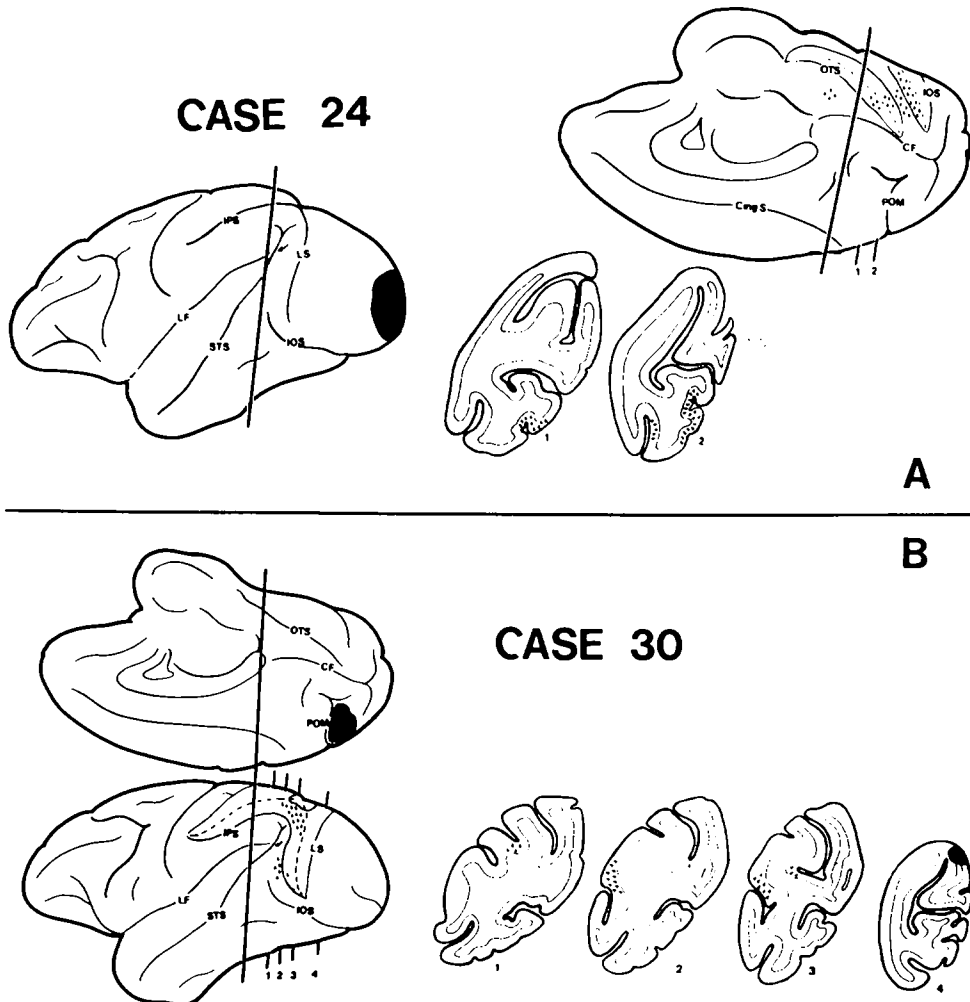


Fig. 7. Diagrammatic representation of HRP-positive neurons in area 18 (and the STS) following an injection of area 17 in the occipital pole and in the depth of the calcarine fissure (A), and in area 19 (and STS) after an injection in a medial part of area 18 (B). Neurons in other cortical regions are not shown.

these cases silver grains were found in the same sectors of area 18 which, as described above, send efferents to these particular sites within area 19. Thus, in cases 27 and 28 (not illustrated), label was concentrated in the posterior bank of the lunate sulcus, while in cases 25 (Fig. 6B) and 26 (not illustrated), with more dorsal injections, label occurred more dorsally in the annectent gyrus and on the medial surface (cf. isotope cases 9-11; Figs. 4 and 6). An injection in the ventral part of area 19 (as in case 29) produced label predominantly in the posterior part of the inferior occipital gyrus. Some of these cases also resulted in smaller concentrations of grains in the opposite quadrant of area 18. For example in case 25, with an injection in the mid portion of the preoccipital gyrus, some grains were seen not only dorsally, but also *ventrally*, in the

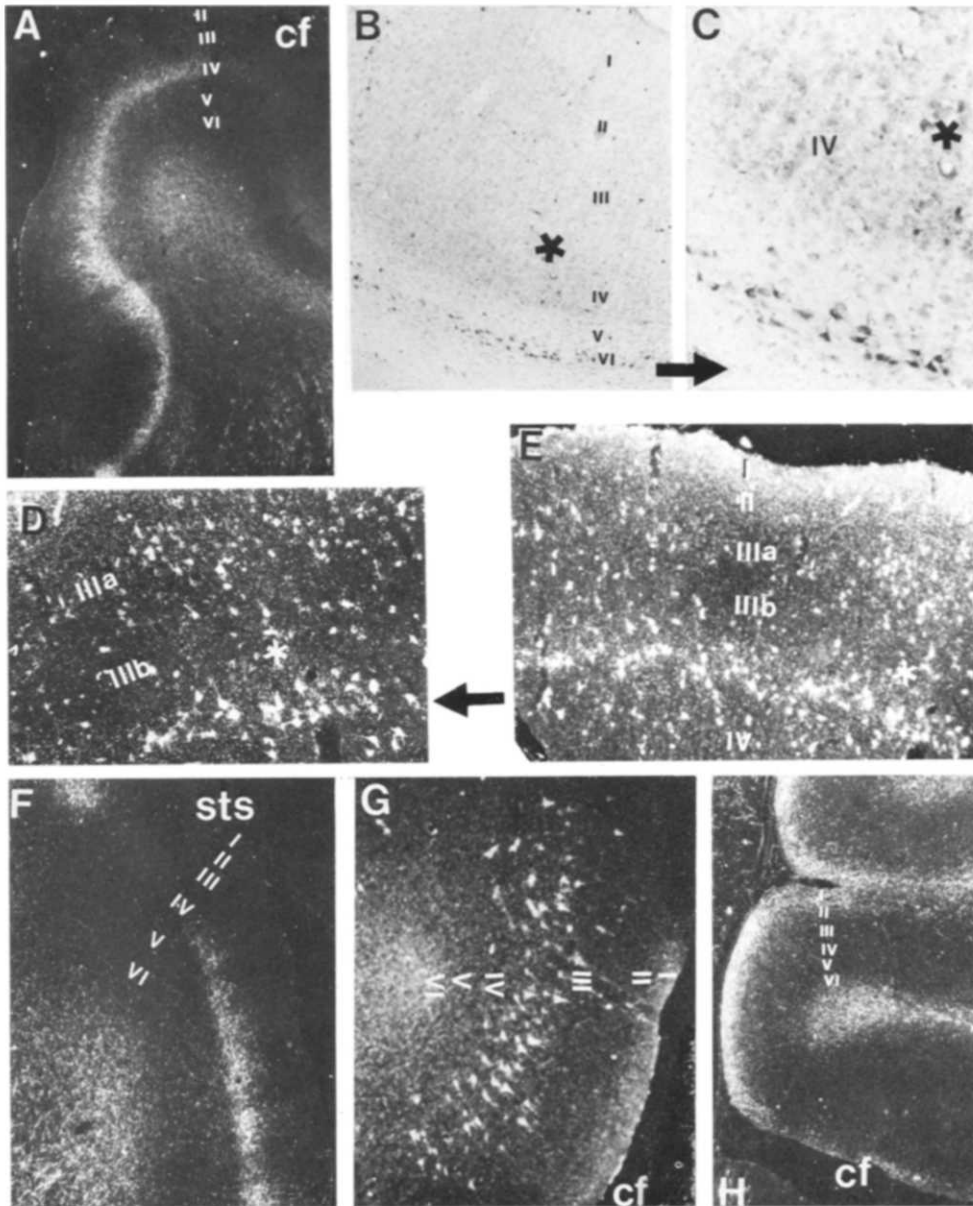


Fig. 8. Photomicrographs showing A: silver grains in and around layer IV of area 18, dorsal to the OTS, after an isotope injection in striate cortex in the depth of the calcarine fissure (case 4) ( $\times 9$ ). B ( $\times 35$ ) and C ( $\times 150$ ): HRP-positive neurons in layer VI of area 18 in the OTS, following an injection of striate cortex at the depth of the calcarine fissure (case 24); D ( $\times 90$ ) and E ( $\times 60$ ): filled neurons in layer IIIc/IVb of area 17 in the occipital pole after an HRP injection in area 18 in the annectent gyrus (case 7). F: silver grains in and around layer IV of area 19 in the preoccipital gyrus after an isotope injection in area 18 in the annectent gyrus (case 10) ( $\times 25$ ). G: HRP-positive neurons in layer III of area 18 on the medial surface after an injection in area 19 in the preoccipital gyrus (case 15) ( $\times 60$ ). H: grains predominantly in layer I of area 18 in the POMS after an isotope injection in area 19 in the preoccipital gyrus (case 25) ( $\times 9$ ).

posterior part of the occipito-temporal sulcus (Fig. 6B). In case 29, with a ventral injection, besides the main ventral focus, a few grains appeared *dorsally* within the annectent gyrus.

## 2. HRP injection

In case 30, HRP was injected into that part of area 18 lying on the medial surface of the hemisphere along the caudal bank of the POMS. There was some spread of HRP into the annectent gyrus, as well as into adjoining striate cortex. As shown in Fig. 7B, HRP-positive neurons occurred in two foci in area 19; namely, within the preoccipital gyrus and in the anterior bank of the lunate sulcus. These foci closely corresponded to the location of silver grains in cases 10 and 11 (see Figs. 4B and 6A), with isotope injections in the same region as the HRP injection site in the present case. In addition, case 30 had HRP-positive neurons in the superior temporal sulcus, in a region previously shown to contain silver grains after isotope injections in medial parts of area 18 (see cases 10 and 11).

## Laminar organization

The use of both the autoradiographic and HRP procedures in the present experiments allowed visualization of the precise laminae of termination and of origin of the above described connections. Since these laminar patterns have been detailed in a previous report<sup>23</sup>, they will only be briefly mentioned here. Projections from area 17 to area 18, and to the superior temporal sulcus (STS), terminate primarily in layer IV, with some grains in layer III as well (Fig. 8A). Similarly, efferents from area 18 to area 19, and to the STS, also terminate in and around layer IV (Fig. 8F). In contrast, connections from area 18 to area 17, and from area 19 to area 18, are directed mainly to layer I of the target zone. Lesser concentrations of label occur in layers IIIC and V of area 17, and in layers V and VI of area 18 (Fig. 8H). With regard to the laminar location of cells of origin, neurons projecting from area 17 to area 18 are visualized in layers IIIA and IIIC/IVB (Fig. 8D and E), while those projecting to the STS are situated mainly in layer IIIC/IVB as well as in layer VI. Neurons in area 18 giving rise to projections to area 19 occur in layer III of area 18 (Fig. 8G). Finally, the neurons projecting caudally (i.e. from area 18 to area 17, from area 19 to area 18, and from the STS to both areas 18 and 17) are found predominantly in layers VB and VI, with a few also scattered in layer IIIA (Fig. 8B and C).

## DISCUSSION

### *Topographic connections from area 17 to area 18*

Previous investigations have shown that striate cortex is topographically connected with the surrounding prestriate region<sup>6,13,19,31,39</sup>. The present report indicates that the rostral part of area 17 on the occipital convexity is connected with area 18 in the lunate sulcus (its posterior bank and depth, as well as the anterior bank of its ventral tip), and that projections from progressively more caudal striate cortex are directed to area 18 in the annectent gyrus (from the dorsal part of the occipital pole) and in the

inferior occipital sulcus (from the ventral part of the occipital pole). The present investigations further demonstrate, as shown in Fig. 9, that medial area 17 in the upper bank of the calcarine fissure projects to the annectent gyrus, immediately medial and adjacent to the connections from the dorsal occipital pole. In contrast, area 17 in the lower calcarine bank is primarily connected with ventral prestriate cortex in the occipito-temporal sulcus and adjoining inferior occipital gyrus. The borders of this striate-recipient zone closely correspond to the architectonically delineated area OB of Bonin and Bailey or area 18 of Vogt and Vogt.

Several previous reports suggested that striate cortex<sup>46</sup>, or striate cortex along with the adjacent prestriate cortex<sup>6</sup>, project beyond the lunate sulcus to the ventral preoccipital gyrus. In agreement with the findings of Van Essen et al.<sup>33</sup>, our material

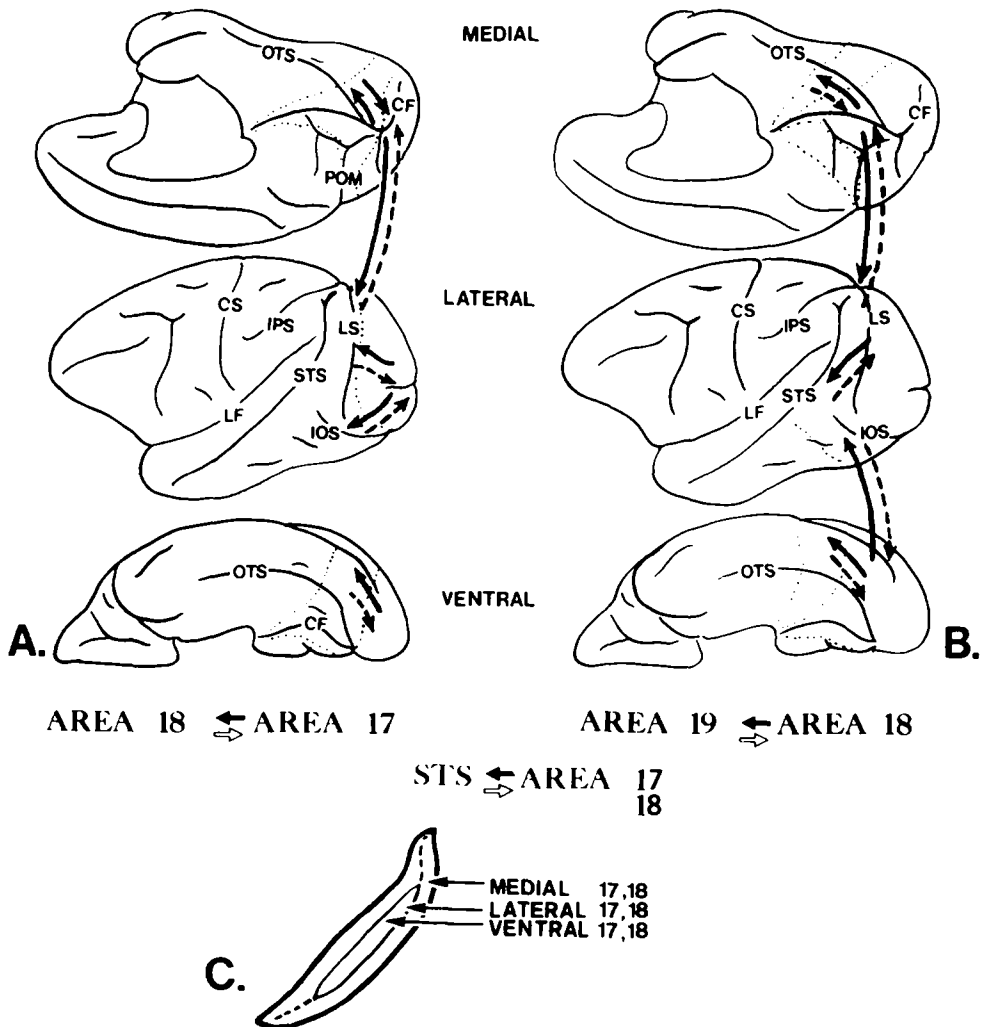


Fig. 9. Summary diagram showing the topographic organization of connections between A: areas 17 and 18, B: 18 and 19, and C: from areas 17 and 18 to the superior temporal sulcus.



indicates that projections from foveal striate cortex (located in the ventrolateral margin of the occipital convexity) are confined mainly to the ventral tip of the lunate sulcus (see case 1, Fig. 1A). We failed to observe direct striate projections to the preoccipital gyrus. This preoccipital area instead is found to receive dense connections from area 18 in the posterior bank of the lunate sulcus (see cases 9 and 17, Figs. 4A and 5B).

#### *Internal organization of area 18*

Recent physiological mapping experiments indicate that area 18, like area 17, is visuotopically organized<sup>9,32,33,43</sup>. As in striate cortex (VI), the foveal representation in area 18 (V2) is located ventrolaterally in the occipital lobe; the lower visual field is situated dorsally; and the upper visual field is represented ventrally. The topographically organized connections between areas 17 and 18, as described in the present report and in other combined anatomico-physiological studies of the lunate sulcus<sup>39,43</sup>, appear to interlink similar visual field points in these two cortical areas.

This systematic visuotopic correspondence between points in areas 17 and 18 has proved useful in elucidating the internal structure of area 18. As shown by Zeki et al.<sup>32,39,43,45</sup>, lesions in striate cortex, restricted to the horizontal or vertical meridian representations, reveal projections to horizontal or vertical meridian representations in prestriate cortex. According to these studies, the striate-recipient belt is bordered by two representations of the vertical meridian. These representations are interpreted as denoting, respectively, the posterior and anterior boundaries of two distinct visuotopically organized areas, V2 and V3. In our material, a patchy organization of striate projections was observed in the posterior bank of the lunate sulcus, as seen in case 1 (Fig. 1A). This patchiness could correspond to the two representations described by Zeki. It may also, however, reflect discontinuities between the multiple injection sites in this case since similar patchiness was not evident in other cases. In particular, injections in the occipital pole, in the depth of the calcarine fissure, and a small injection of the ventral calcarine lip all resulted in apparently single projection zones within area 18 (see cases 2, 4 and 5; Figs. 1B, 2A and 2B).

Recently, direct connections have been reported from striate cortex in the calcarine fissure to a separate visual area, V3A, in the parieto-occipital sulcus<sup>47</sup>. This area lies within the striate-recipient zone outlined by the present experiments, but appears to be a direct continuation of the striate-recipient belt in the lunate sulcus and annectent gyrus (see cases 1 and 2; Fig. 1). More evidence from combined anatomico-physiological studies is necessary to establish whether this V3A region contains a separate representation of the visual field.

#### *Topographic connections from area 18 to area 19*

In agreement with earlier observations, area 18 is found to project to anterior prestriate cortex<sup>6,13,41</sup>, which closely corresponds with the architectonically designated area OA or area 19. Connections from area 18 to this zone are topographically organized, although these efferents are not directed to immediately adjoining parts of area 19. The preoccipital gyrus, for example, receives connections from an elongated

strip of area 18 which not only includes the lunate sulcus, but which also extends well onto the medial surface of the occipital lobe. Thus, the posterior bank of the lunate sulcus is connected only with the ventralmost part of the preoccipital gyrus (see cases 9 and 17; Figs. 4A and 5B), while more medial portions of area 18, around the annectent gyrus, send efferents to its mid-portion (cases 10, 11, and 16; Figs. 4B and 6A). Projections from even more medial portions of area 18, adjoining the calcarine fissure, are directed to the dorsalmost part of the preoccipital gyrus (as in cases 13 and 15; Figs. 4C and 5A).

Medially, as shown in Fig. 9, this area 19 connectional strip continues from the preoccipital gyrus and the lower bank of the intraparietal sulcus, through the annectent gyrus (rostral to the striate-recipient portion) and along the rostral bank of the parieto-occipital sulcus. Ventrally, this 18-recipient strip runs through the inferior occipital sulcus (IOS), along the adjacent gyrus (area TEO)<sup>3</sup>, and extends rostrally into the occipito-temporal sulcus (OTS). Area TEO receives connections mainly from area 18 in the rostral subdivision of the IOS, as well as in the ventral tip of the lunate sulcus. In contrast, area 19 in the OTS and medially adjoining part of the inferior occipital gyrus receives efferents from medial area 18, in the caudal part of the OTS and lower lip of the calcarine fissure (see cases 13 and 18; Figs. 4C and 5C).

#### *Double connections from area 18 to area 19*

In addition to the strict intra-quadrantic topographic arrangement of connections between areas 18 and 19, there is a second set of 'crossed' connections from certain parts of area 18 to area 19. Thus, area 18 in the annectent gyrus, besides its dorsal intra-quadrantic connections with area 19 in the preoccipital gyrus, also projects ventrally to area 19 in the inferior occipital gyrus (see case 10, Fig. 6A, with an injection of dorsal area 18; also case 18, Fig. 5C). Similarly, area 18 in the caudal part of the IOS not only projects to ventral area 19, but also sends projections dorsally to area 19 in the anterior bank of the lunate sulcus and lower bank of the intraparietal sulcus (as in case 14). The significance of these ventral-to-dorsal connections is unclear. It is likely that area 19 in the rhesus monkey, as in the owl monkey, may be composed of several anatomically and visuotopically distinct visual areas. In this case, ventral-to-dorsal crossed connections may afford a means for reuniting the upper and lower parts of the visual field (located respectively within the ventral and dorsal quadrants of area 18) within two separate visual areas, situated in the inferior occipital gyrus and intraparietal sulcus.

#### *Internal organization of area 19*

According to recent investigations using small meridional lesions<sup>41</sup>, areas V2 and V3, two distinct visuotopic areas within architectonically defined area 18, provide the main input to the 'V4 complex' (here called area 19) within the IOS and preoccipital gyrus. While the present experiments did not use a similar meridional approach, the series of HRP injections within area 19 did provide some information as to the organization of afferent connections to this area. These experiments (in cases 15-20) suggested that V2, defined as the juxtastriate cortex and adjacent few

millimeters within area 18, does project in a topographic manner to a region probably coinciding with V4 in the preoccipital gyrus, in a single patch (see cases 9–11; Figs. 4A, 4B and 6A). Additional connections to this V4 area, from cortex probably corresponding to area V3, in the depth of the lunate sulcus, however, were not clearly observed in our material.

#### *Connections to the superior temporal sulcus (STS)*

Our study, as well as several recent reports<sup>18,30,37,40</sup> indicates that projections from striate cortex are directed to an architectonically distinct zone, area OAa<sup>26</sup>, within the STS. These connections terminate in a topographic order which appears to correspond with the physiologically mapped representation of the visual field within the caudal-third of the STS<sup>8,15</sup>. Thus, the connections from the lateral part of striate cortex (representing central vision)<sup>7</sup> are directed to the lower bank and depth of the sulcus, while the medial surface (representing more peripheral vision) sends efferents more rostrally in the sulcus, to its depth and anterior bank.

Connections from area 18 appear to terminate in the same striate-recipient zone in the STS. Like the connections from striate cortex, those from the dorsomedial part of area 18 are directed to the caudalmost part of the sulcus (representing the lower visual field), while those from the lateral and ventral surfaces are connected with progressively more rostral portions of the sulcus (representing central vision and the upper visual field). These findings confirm earlier observations of Zeki<sup>44</sup>, based on combined autoradiographic–degeneration experiments, suggesting that connections from both areas 17 and 18 are directed to the same part of the STS. The connections from both areas 17 and 18 to the STS are reciprocal in nature (see cases 24 and 30; Fig. 7), as previously indicated<sup>27,37</sup>.

Connections from the lateral portion of area 17, as well as of area 18, are considerably stronger than those from more medial and ventral regions, as suggested earlier by Cragg<sup>6</sup>. Since these portions of area 17 and 18 contain central visual field representations<sup>7,9,33</sup>, the particularly dense connections from these areas may imply that the striate-recipient portion of the STS is preferentially involved in central visual processes. This possibility is supported by recent physiological mapping experiments<sup>8,15</sup>, which indicate that a large portion of the visual area in the STS is devoted to the central visual field.

#### *Caudally directed connections*

Point-to-point topographic connections have been described from prestriate (area 18) to striate cortex in New World primates<sup>11,14,28,29,38</sup>. Our results, based on injections both of isotopes and HRP, demonstrate that the connections from area 18 to area 17 in the rhesus monkey are also topographically organized. For example, area 18 in the annectent gyrus projects back to area 17 in the dorsal occipital pole (case 10; Fig. 6A) and area 18 in the OTS sends connections back to area 17 in the lower bank of the calcarine fissure (case 24; Fig. 7A). Similarly, area 19 projects back to area 18 in a topographic manner. Thus, the ventral preoccipital gyrus is found to project back to area 18 in the lunate sulcus (cases 27 and 28), and the dorsal preoccipital gyrus sends

effereents back to area 18 on the medial surface (case 25; Fig. 6B). Additionally, those parts of area 19, in the intraparietal sulcus and inferior occipital gyrus, which receive double connections from both the ventral and dorsal parts of area 18 also send crossed connections back to these same areas (cases 25, 26 and 29). The function of these backgoing connections is not clear. Similar backgoing connections have been described from the superior temporal sulcus to area 17<sup>27</sup>, from parasensory cortices to the primary somatosensory and primary auditory areas<sup>20,34</sup>, between non-primary visual areas<sup>36</sup>, and from premotor cortex to the post-Rolandic sensory areas<sup>12</sup>. The widespread occurrence of such connections suggests that these pathways are basic to normal cortical functioning, perhaps subserving a general 'feedback' or gating mechanism.

The orderly topographic arrangement of occipital efferents, as outlined in the present study, indicates the importance of sequential, stepwise connections in sensory cortical processes. This conclusion is also supported by physiological experiments demonstrating the loss of visual responsiveness in area 18 after inactivation of area 17<sup>25</sup>. However, the existence of caudally directed connections from both areas 19 and 18, and of an additional visual region in the superior temporal sulcus, imply that other, non-sequential modes of processing are also important.

#### ACKNOWLEDGEMENTS

This work was carried out in partial fulfillment of requirements for the degree of Doctor of Philosophy from the Division of Medical Sciences at Boston University (K.S.R.). This study was supported by Anatomy Training Grant 5T01 GM01979, NIH Grant NS09211, and V.A. Research Project 6901.

We would like to thank Dr. Benjamin Seltzer for his helpful comments on the manuscript.

#### REFERENCES

- 1 Allman, J. M. and Kaas, J. H., The dorsomedial cortical visual area: a third tier area in the occipital lobe of the owl monkey (*Aotus trivirgatus*), *Brain Research*, 100 (1975) 473-487.
- 2 Bonin, G. von and Bailey, P., *The Neocortex of Macaca mulatta*, University of Illinois Press, Urbana, Ill., 1947.
- 3 Bonin, G. von and Bailey, P., *The Isocortex of the Chimpanzee*, University of Illinois Press, Urbana, Ill., 1950.
- 4 Brodmann, K., Beitrage zur histologischen Lokalisation der Grosshirnrinde. III. Mitteilung: Die Rindenfelder der neideren Affen, *J. Psychol. Neurol. (Lpz.)*, 4 (1905) 177-206.
- 5 Cowan, W. M., Gottlieb, D. I., Hendrickson, A. E., Price, J. L. and Woolsey, T. A., The autoradiographic demonstration of axonal connections in the central nervous system, *Brain Research*, 37 (1972) 21-51.
- 6 Cragg, B. G. and Ainsworth, A., The topography of the afferent projections in the circumstriate visual cortex of the monkey studied by the Nauta method, *Vision Res.*, 9 (1969) 733-747.
- 7 Daniel, P. M. and Whitteridge, D., The representation of the visual field on the cerebral cortex in monkeys, *J. Physiol. (Lond.)*, 159 (1961) 203-221.
- 8 Gattass, R. and Gross, C. G., A visuotopically organized area in the posterior superior temporal sulcus of the macaque, *ARVO Abstr.*, (1979) 184.
- 9 Gattass, R., Sandell, J. H. and Gross, C. G., V2 in the macaque monkey: visuotopic organization and extent, *Neurosci. Abstr.*, 5 (1979) 786.

- 10 Graham, R. C., Jr. and Karnovsky, M. J., The early stages of absorption of injected horseradish peroxidase in the proximal tubules of mouse kidney: ultrastructural cytochemistry by a new technique, *J. Histochem. Cytochem.*, 14 (1966) 291–299.
- 11 Kaas, J. H. and Lin, C. S., Cortical projections of area 18 in owl monkeys, *Vision Res.*, 17 (1977) 739–741.
- 12 Kunzle, H., An autoradiographic analysis of the efferent connections from premotor and adjacent prefrontal regions (areas 6 and 9) in *Macaca fascicularis*, *Brain Behav. Evol.*, 15 (1978) 185–234.
- 13 Kuypers, H. G. J. M., Szwarcbart, M. K., Mishkin, M. and Rosvold, H. E., Occipitotemporal cortico-cortical connections in the rhesus monkey, *Exp. Neurol.*, 11 (1965) 245–262.
- 14 Martinez-Millan, L. and Hollander, H., Cortico-cortical projections from striate cortex of the squirrel monkey (*Saimiri sciureus*), A radioautographic study, *Brain Research*, 83 (1975) 405–417.
- 15 Maunsell, J. H. R., Bixby, J. L. and Van Essen, D. C., The middle temporal area (MT) in the macaque: architecture, functional properties and topographic organization, *Neurosci. Abstr.*, 5 (1979) 796.
- 16 Mesulam, M.-M., The blue reaction product in horseradish peroxidase neurohistochemistry: incubation parameters and visibility, *J. Histochem. Cytochem.*, 24 (1976) 1273–1280.
- 17 Mesulam, M.-M., Tetramethylbenzidine for horseradish peroxidase neurohistochemistry: a non-carcinogenic blue reaction-product with superior sensitivity for visualizing neural afferents and efferents, *J. Histochem. Cytochem.*, 26 (1978) 106–117.
- 18 Montero, V. M., Patterns of connections from the striate cortex to cortical visual areas in superior temporal sulcus of macaque and middle temporal gyrus of owl monkey, *J. comp. Neurol.*, 189 (1980) 45–60.
- 19 Myers, R. E., Organization of visual pathways. In E. G. Ettliger (Ed.), *Functions of the Corpus Callosum*, Churchill, London, 1965, pp. 133–143.
- 20 Pandya, D. N. and Sanides, F., Architectonic parcellation of the temporal operculum in rhesus monkey and its projection pattern, *Z. Anat. Entwickl.-Gesch.*, 13 (1973) 127–161.
- 21 Rockland, K. S. and Pandya, D. N., Cortical afferents to ventral peristriate cortex (area TEO) in rhesus monkey, *Anat. Rec.*, 187 (1977) 696.
- 22 Rockland, K. S. and Pandya, D. N., Connections from prestriate cortex to the superior temporal sulcus in the rhesus monkey, *Neurosci. Abstr.*, 5 (1979a) 805.
- 23 Rockland, K. S. and Pandya, D. N., Laminar origins and terminations of cortical connections of the occipital lobe in the rhesus monkey, *Brain Research*, 179 (1979b) 3–20.
- 24 Rosene, D. L. and Mesulam, M.-M., Fixation variables in horseradish peroxidase neurochemistry: effects of perfusion and post-fixation on sensitivity, *J. Histochem. Cytochem.*, 26 (1978) 28–39.
- 25 Schiller, P. H. and Malpeli, J. G., The effect of striate cortex cooling on area 18 cells in the monkey, *Brain Research*, 126 (1977) 366–369.
- 26 Seltzer, B. and Pandya, D. N., Afferent cortical connections and architectonics of the superior temporal sulcus and surrounding cortex in the rhesus monkey, *Brain Research*, 149 (1978) 1–24.
- 27 Spatz, W. B., Topographically organized reciprocal connections between areas 17 and MT (visual area of the superior temporal sulcus) in the marmoset, *Callithrix jacchus*, *Exp. Brain Res.*, 27 (1977) 559–572.
- 28 Tigges, J., Spatz, W. B. and Tigges, M., Reciprocal point-to-point connections between parastriate and striate cortex in the squirrel monkey (*Saimiri*), *J. comp. Neurol.*, 148 (1973) 481–490.
- 29 Tigges, J., Spatz, W. B. and Tigges, M., Efferent cortico-cortical fiber connections of area 18 in the squirrel monkey (*Saimiri*), *J. comp. Neurol.*, 158 (1974) 219–236.
- 30 Ungerleider, L. and Mishkin, M., The striate projection zone in the superior temporal sulcus of *Macaca mulatta*: location and topographic organization, *J. comp. Neurol.*, 188 (1979) 347–366.
- 31 Ungerleider, L. and Mishkin, M., Three cortical projection fields of area 17 in the rhesus monkey, *Neurosci. Abstr.*, 5 (1979) 812.
- 32 Van Essen, D. C. and Zeki, S. M., The topographic organization of rhesus monkey prestriate cortex, *J. Physiol. (Lond.)*, 277 (1978) 193–226.
- 33 Van Essen, D. C., Maunsell, J. H. R. and Bixby, J. L., Areal boundaries and topographic organization of visual areas V2 and V3 in the macaque monkey, *Neurosci. Abstr.*, 5 (1979) 812.
- 34 Vogt, B. A. and Pandya, D. N., Cortico-cortical connections of somatic sensory cortex (areas 3, 1 and 2) in the rhesus monkey, *J. comp. Neurol.*, 177 (1978) 179–192.
- 35 Vogt, C. and Vogt, O., Allgemeinere Ergebnisse unserer Hirnforschung, *J. Psychol. Neurol. (Lpz.)*, 25 (1919) 279–461.
- 36 Wagor, E., Lin, C. S., and Kaas, J. H., Some cortical projections of the dorsomedial visual area

- (DM) of association cortex in the owl monkey (*Aotus trivirgatus*), *J. comp. Neurol.*, 163 (1975) 227–250.
- 37 Weller, R. E. and Kaas, J. H., Connections of striate cortex with the posterior bank of the superior temporal sulcus in macaque monkeys, *Neurosci. Abstr.*, 4 (1978) 650.
  - 38 Wong-Riley, M., Reciprocal connections between striate and prestriate cortex in squirrel monkey as demonstrated by combined peroxidase histochemistry and autoradiography, *Brain Research*, 147 (1978) 159–164.
  - 39 Zeki, S. M., Representation of central visual fields in prestriate cortex of monkey, *Brain Research*, 14 (1969) 271–291.
  - 40 Zeki, S. M., Convergent input from the striate cortex (area 17) to the cortex of the superior temporal sulcus in the rhesus monkey, *Brain Research*, 28 (1971) 338–340.
  - 41 Zeki, S. M., Cortical projections from two prestriate areas in the monkey, *Brain Research*, 34 (1971) 19–35.
  - 42 Zeki, S. M., Functional organization of a visual area in the posterior bank of the superior temporal sulcus of the rhesus monkey, *J. Physiol. (Lond.)*, 236 (1974) 549–573.
  - 43 Zeki, S. M., The functional organization of projections from striate to prestriate visual cortex in the rhesus monkey, *Cold Spr. Harb. Symp. quant. Biol.*, 40 (1975) 591–600.
  - 44 Zeki, S. M., The projections to the superior temporal sulcus from areas 17 and 18 in the rhesus monkey, *Proc. roy. Soc. B*, 193 (1976) 199–207.
  - 45 Zeki, S. M., Simultaneous anatomical demonstration of the representation of the vertical and horizontal meridians in areas V2 and V3 of rhesus monkey visual cortex, *Proc. roy. Soc. B*, 195 (1977) 517–523.
  - 46 Zeki, S. M., The cortical projections of foveal striate cortex in the rhesus monkey, *J. Physiol. (Lond.)*, 277 (1978) 227–244.
  - 47 Zeki, S. M., A direct projection from area V1 to area V3A of rhesus monkey visual cortex, *Proc. roy. Soc. B*, 207 (1980) 499–506.