Published in final edited form as:

J Comp Neurol. 2012 June 15; 520(9): 2002–2020. doi:10.1002/cne.23025.

Cortical Projections to the Superior Colliculus in Prosimian Galagos (*Otolemur garnetti*)

Mary K.L. Baldwin and Jon H. Kaas*

Department of Psychology, Vanderbilt University, Nashville, Tennessee 37240

Abstract

The superior colliculus (SC) is a key structure within the extrageniculate pathway of visual information to cortex and is highly involved in visuomotor functions. Previous studies in anthropoid primates have shown that superficial layers of the SC receive direct inputs from various visual cortical areas such as V1, V2, and middle temporal (MT), while deeper layers receive direct inputs from visuomotor cortical areas within the posterior parietal cortex and the frontal eye fields. Very little is known, however, about the corticotectal projections in prosimian primates. In the current study we investigated the sources of cortical inputs to the SC in prosimian galagos (*Otolemur garnetti*) using retrograde anatomical tracers placed into the SC. The superficial layers of the SC in galagos received the majority of their inputs from early visual areas and visual areas within the MT complex. Yet, surprisingly, MT itself had relatively few corticotectal projections. Deeper layers of the SC received direct projections from visuomotor areas including the posterior parietal cortex and premotor cortex. However, relatively few corticotectal projections originated within the frontal eye fields. While prosimian galagos resemble other primates in having early visual areas project to the superficial layers of the SC, with higher visuomotor regions projecting to deeper layers, the results suggest that MT and frontal eye field projections to the SC were sparse in early primates, remained sparse in present-day prosimian primates, and became more pronounced in anthropoid primates.

INDEXING TERMS

visual cortex; FEF; LIP; MT; primates

The present study is part of an extended effort to compare and contrast the organization of visual systems across members of the two major branches of the primate radiation, the prosimians and the anthropoids. The cortical distributions of neurons projecting to the superior colliculus (SC) has been studied in both New World monkeys (Cusick, 1988; Collins et al., 2005a,b) and Old World monkeys (Fries et al., 1984, 1985; Lock et al., 2003), but not in any prosimians. In both New World and Old World monkeys, early visual areas, including the first, second, and third visual areas (V1, V2, and V3, respectively), as well as the middle temporal visual area (MT) project densely to the superficial layers of the SC, while visuomotor areas of posterior parietal cortex and frontal cortex, in particular, the frontal eye fields (FEF), project densely to the deeper layers. Additionally, projections from parts of prefrontal cortex, in addition to the FEF, have been reported in macaques and cebus monkeys (Goldman and Nauta, 1976; Leichnetz et al., 1981; Fries, 1984, 1985; Johnston

and Everling, 2006, 2009; Pouget et al., 2009). There are few cortical projections from auditory, somatosensory, higher order multisensory, motor, and cingulate areas to the SC.

The main goal of the current study was to determine corticotectal projections to the SC in prosimian galagos and to relate our findings to those from simian primates. Extant prosimian primates more closely resemble early primates in brain size relative to body size than do anthropoid primates (Le Gros Clark, 1931; Radinsky, 1975; Stephan et al., 1981; Jerison, 2007), and their cortical organization may more clearly reflect that of the early ancestors of all primates (Kaas, 2007). Comparing data from prosimian galagos to information from anthropoids, therefore, provides a means of identifying brain features that are either shared with anthropoid primates or are possibly specializations of one or the other main branches of the primate radiation.

Cortical organization has been extensively studied in prosimian galagos and many of the cortical areas with projections to the SC in anthropoid primates have been anatomically and physiologically described in galagos. For instance, subdivisions of frontal cortex have been defined, including the FEF (Wu et al., 2000), as have sensorimotor regions of posterior parietal cortex (Stepniewska et al., 2005, 2009a,b). Additionally, recent evidence has shed light on the organization of some of the early visual areas, especially V3 (Lyon and Kaas, 2002) and areas that are part of the MT complex (Kaskan and Kaas, 2007). Yet, little is known about the connections of these areas with the SC.

In the present study, afferent connections to the SC in galagos were studied by injections of retrograde anatomical tracers into the SC. We were able to examine differences in the distributions of corticotectal neurons labeled by superficial and deep injections and by injections into different topographic locations in the SC. The results revealed some expected similarities in the distributions of corticotectal projections in primates. Most notably, projections to the superficial layers of the SC were largely from early visual areas. The locations of labeled corticotectal neurons were primarily in topographic locations within the visual areas that matched those of the injection sites. In addition, single injections in the SC labeled patches of neurons at several locations in temporal visual cortex, a region where the functional subdivisions are poorly understood in galagos. Unexpectedly, only a few corticotectal projections originated from MT and injections of tracers in locations that included the deeper layers of the SC labeled few neurons in the locations of FEF.

MATERIALS AND METHODS

In order to reveal distributions of corticotectal projections, five adult galagos (*Otolemur garnetti*) received injections of retrogradely transported tracers in the SC. All surgical procedures were in accord with an approved protocol under the Vanderbilt University Institutional Animal Care and Use committee and followed guidelines published by the National Institutes of Health. Injections placed in the SC labeled neurons in neocortex, which were plotted and related to cortical areas.

Surgical procedures and injections

Surgical procedures were similar to those of Baldwin et al. (2011). In brief, galagos were initially anesthetized with an intramuscular (IM) injection of ketamine hydrochloride (120 mg/kg) and maintained under anesthesia using isoflurane anesthesia (1–3%) through a tracheal tube. Lidocaine was placed in both ears as well as along the midline of the scalp and heads were held in a stereotaxic frame. Heart rate, O₂ and CO₂ levels, and body temperature were monitored and recorded throughout the surgery. The scalp was cut along the midline and retracted to expose the skull. A craniotomy over the left parietal and occipital lobes was placed to expose the caudal half of the intraparietal sulcus and the medial occipital lobe. The

dura was reflected and enough caudomedial cortex was removed by aspiration to allow the medial surface of the left SC to be visualized (Fig. 1). The right hemisphere was then retracted slightly to expose the medial aspect of the right SC (Fig. 1C). Then 0.2–0.75 μ l of cholera toxin B-subunit (CTB: Molecular Probes Invitrogen, Carlsbad, CA; 10% in distilled water) and/or 0.2–0.75 μ l of fluoro-ruby (FR: Molecular Probes Invitrogen; 10% in 0.1M phosphate buffer) were pressure-injected at separate sites into the medial portion of the SC using a Hamilton syringe outfitted with a beveled glass pipette tip. Any leakage of tracer to the SC surface during injections was removed with sterile saline flushes to prevent tracer contamination of surrounding brain tissue. After injections, gelfoam was placed into the lesion site, gelfilm was then placed over the brain, the craniotomy was closed using dental cement, and the scalp was sutured. Animals were then taken off anesthesia, given Buprenex (0.3 mg/kg IM) for analgesic, and monitored during recovery.

In one case, 09–34, 7 days after the initial surgery, we conducted a microstimulation experiment within the right frontal cortex to identify the FEF. In this case the galago was anesthetized with an IM injection of ketamine hydrochloride (120 mg/kg) and during surgical procedures was maintained under anesthesia using isoflurane (1–3%). For the microstimulation session the anesthesia was changed to a mixture of ketamine hydrochloride (30–60 mg/kg/hr intravenously) and xylazine (0.4 mg/kg IM). A craniotomy was placed over the frontal lobe to expose the frontal sulci (FS). A low-impedance tungsten microelectrode (1.0 M Ω) was mounted on an electrode holder and oriented perpendicular to the cortical surface. The electrode was then lowered into the brain anterior and ventral to the FS and monophasic pulses of 0.2 msec of electrical current were delivered in 60-msec trains at 300 Hz. The FEF was identified as the region of the cortex that elicited eye movements during stimulation. Most eye movements were elicited with thresholds of 65–150 μ A. The mapping session was kept short (5–6 hours) to minimize damage to the cortex. After the FEF was mapped, four electrolytic lesions were placed along its borders and then the galago was sacrificed with an overdose of sodium pentobarbital.

Tissue processing and data analysis

After 5–7 days of survival, galagos were sacrificed using an overdose of sodium pentobarbital (80 mg/kg) and perfused with phosphate-buffered saline (PBS: pH 7.4) followed by 2% paraformaldehyde, and finally with a solution of 2% paraformaldehyde with 10% sucrose. The brains were removed, the cortex was separated from underlying brain structures, the sulci were opened, and the brain was flattened as described in Krubtizer and Kaas (1990). Both cortex and thalamus with brainstem were placed in 30% sucrose solutions at 4°C for 20–48 hours. The right flattened cortex was cut parallel to the cortical surface on a freezing microtome at a thickness of 40 μ m, while the brainstem was cut coronally at a thickness of 40 μ m. Alternating sections were processed to reveal tracer label and cortical architecture. The cortical sections were divided into four series and processed for cytochrome oxidase (CO; Wong-Wiley, 1979), myelin (Gallyas, 1979), or CTB using a protocol described in Baldwin et al. (2011) (Table 1). The last series was not processed, but instead mounted directly onto slides and coverslipped for fluorescent analysis of neurons labeled with FR. The brainstem was processed in five series, which were CO, CTB, FR, and acetylcholinesterase (AChE: Geneser-Jensen and Blackstand, 1971); the fifth series was set aside and processed as part of another study. Here we describe only the results from cortex and the locations of injections in the SC.

To determine the locations of retrogradely labeled cells, CTB and FL sections were plotted using a Neurolucida system (MicroBrightField, Williston, VT).

Brainstem sections stained for CO and AChE were used to identify the layers of the SC. Injection sites were illustrated on dorsal views of the SC surface, which were reconstructed

from coronal brain sections and matched with photographs of the SC taken during brain dissection. Cortical sections plotted for labeled neurons were aligned with adjacent sections stained for cortical architecture using common blood vessels and other features. Alignments were made locally in order to most accurately relate plotted neurons to architectonic fields. The borders of some cortical areas (V1, V2, MT, 3b, A1) were determined architectonically using CO or myelin-stained sections (see below), or were estimated based on locations and relationships to sulci and other cortical areas determined in previous studies on galago cortical organization. Finally, numbers of cells within cortical areas were counted in Adobe Illustrator (San Jose, CA) using Document Info settings. Photographs of tissue sections were taken using a DMX1200F digital camera mounted to a Nikon E800S microscope (Melville, NY). Photomicrographs were adjusted for brightness and contrast using Adobe Photoshop, but were otherwise not altered.

Locations of injection sites

Injection sites and tracer spread were related to the layers of the SC identified in CO and AChE-stained sections (Fig. 2) and to the representation of the contralateral visual hemifield in the SC. The SC has seven main layers (May, 2006), which include the stratum zonale (SZ), the stratum griseum superficiale (SGS), stratum opticum (SO), stratum griseum intermediale (SGI), stratum album intermediale (SAI), stratum griseum profundum (SGP), and stratum album profundum (SAP) (Fig. 2). Although the SGS and SGI have been subdivided further (Balaram et al., 2011), we did not subdivide these layers in the current study. SZ, SGS, and SO are parts of the superficial SC, which has been primarily associated with visual sensory functions. The intermediate (SGI and SAI) and deep (SGP and SAP) layers have been attributed to sensorimotor integration and various motor functions.

SC injections that involved SZ, SGS, SO, and the most superficial aspect of the SGI are described in our superficial and intermediate injection section cases. These types of injections were observed for cases 07–105, 07–111, and 08–40. For all of these cases the injection site cores were within the SGS, but the injection site spread included SGS, SO, and the upper aspect of the SGI. Although injection sites did include portions of the upper SGI in these cases, for simplicity we listed and grouped such injections in our Results section as “superficial” injections. Cases 09-03 and 09–34 had SC injection sites that involved layers below the SGI and are therefore grouped into our Results section describing deep layer injections; however, it is important to note that these cases had tracer spread into the superficial layers of the SC.

The visuotopic organization of the SC in galagos has been determined using microelectrode recording experiments (Lane et al., 1973). The lateral SC represents the lower visual field while the upper visual field is represented medially; peripheral vision is represented caudally and central vision rostrally. All topographic determinations of injection site locations were based on estimates, after dorsal reconstructions of the injection site, and by comparing such locations with the topographic maps described in Lane et al. (1973). Most of our injections were within the representation of the upper visual field in the SC, and only one CTB injection included representations of both upper and lower visual fields.

Overlying cortical tissue was analyzed for possible tracer contamination both during brain dissection as well as within our processed tissue sections. We did not notice signs of cortical contamination, and believe that our results reflect corticotectal connections and not corticocortico connections.

Identification of cortical areas

Cortical areas examined in this study within the occipital cortex are V1, V2, V3, DM, and DL (Fig. 1A). Area V1 was reliably identified in galagos by its characteristic CO blob-interblob pattern of staining and dark myelination (Condo and Casagrande, 1990; Kaskan and Kaas, 2007; Wong and Kaas, 2010). V2, rostral to V1, stains less darkly for myelin and, unlike anthropoid primates, has only a weak stripe-like pattern of CO staining at best (Condo and Casagrande, 1990; Kaskan and Kaas, 2007; Wong and Kaas, 2010). Thus, the rostral border of V2 was estimated by its known width. The width of V2 is variable across its length measuring 1 mm near central vision and extending out to 2–3 mm wide at peripheral positions (Rosa et al., 1997; Collins et al., 2001). Determining the borders of V3 was difficult because of the lack of clear anatomical landmarks; however, V3 stains moderately for myelin and darkly for CO and is located along the rostral border of V2. V3's width varies along its length, but it can be as wide as 2 mm in the periphery (Lyon and Kaas, 2002; Wong and Kaas, 2010). DM is located along the rostral border of dorsal V3 and stains moderately for myelin (Krubitzer and Kaas, 1990; Beck and Kaas, 1998a,b; Wong and Kaas, 2010), but more so than bordering areas, except for V3. The full mediolateral extent of DL (V4) is uncertain, therefore we designated the cortical region between V3, MTc, IT, and DM as DL (Fig. 1A). Within V1, V2, V3, and DL, the upper visual hemifield is represented ventrally and the lower visual hemifield is represented dorsally (Rosa et al., 1997; Lyon and Kaas, 2002). The precise topographic organization of DM is not fully known, but DM represents both the upper and lower visual hemifields (Lyon and Kaas, 2002).

Temporal cortex was divided into the following areas: MT, MTc, MST, and FST, IT, and the auditory region (Aud). MT can be identified from surrounding cortical areas by its characteristic dense myelination and heavy CO staining relative to surrounding cortex (Allman et al., 1973; Symonds and Kaas, 1978; Wall et al., 1982; Krubitzer and Kaas 1990; Collins et al., 2001; Kaskan and Kaas, 2007; Wong and Kaas, 2010). Within MT, the upper visual field is represented ventrally and the lower visual field is represented dorsally with central vision caudal and peripheral vision rostral (Allman et al., 1973). The medial superior temporal area, MST, is located just rostral to MT and stains darkly for CO and moderately for myelin (Maunsell and Van Essen, 1983; Weller and Kaas, 1984; Krubitzer and Kaas, 1990; Wong and Kaas, 2010). The fundal area of the superior temporal sulcus, FST, is just ventral to MT. As galagos do not have a superior temporal sulcus, FST is on the cortical surface. FST stains moderately for myelin and CO (Krubitzer and Kaas, 1990; Kaskan and Kaas, 2007; Wong and Kaas, 2010). This area has been divided into ventral, FSTv, and dorsal, FSTd, divisions (Kaas and Morel, 1993); however, we do not distinguish divisions in the present report. The topographic organizations of FST and MST are not well understood but it is thought that MT and MST have adjoining representations of peripheral vision. MTc is distinguishable as a narrow strip of cortex that borders dorsal, caudal, and ventral portions of MT and stains heterogeneously for myelin and CO (Tootell et al., 1985; Kaas and Morel, 1993; Kaskan and Kaas, 2007; Wong and Kaas, 2010). We defined IT as the region of cortex ventral to the MT complex, rostral to DL, and caudal to auditory cortex including space for proposed belt and parabelt auditory cortex (Fig. 1A). There are likely several cortical areas within IT (Zilles et al., 1979; Preuss and Goldman-Rakic, 1991a; Wong and Kaas, 2010), but for simplicity we present our results with respect to a single IT region. Finally, an auditory primarylike region was identified as a darkly stained region in myelin and CO preparations, spanning the caudal bank and lip of the lateral sulcus (Brugge, 1982; Wong and Kaas, 2010).

Parietal cortex includes the primary somatosensory area (3b/S1), posterior parietal cortex (PPC), and the parietal ventral/secondary somatosensory region (PV/S2). We defined posterior parietal cortex as the region of cortex surrounding the IPS, rostral to DM, caudal to 3b/S1, and dorsal to MT, MST, and MTc (Fig. 1A). 3b/S1 was easily identified by its dense

CO and myelin staining pattern (Wu and Kaas, 2003). PV/S2 lies along the rostral bank of the lateral sulcus and stains moderately for CO and myelin (Wu and Kaas, 2003; Wong and Kaas, 2010).

Primary motor cortex is rostral to somatosensory cortex and is characterized by moderate myelin and CO staining (Wong and Kaas, 2010). Dorsal premotor cortex (PMD) and ventral premotor cortex (PMV) were demarcated as the regions of frontal cortex rostral to motor cortex and either dorsal or ventral to the frontal sulci. FEF was determined in one case physiologically and was placed in other cases in its expected location, slightly dorsal to the rostral tip to the frontal sulci (Wu et al., 2000). Finally, based on the results of Wong et al. (2010), granular frontal (Gr) cortex was defined as the region of cortex rostral to the frontal sulcus dorsally, and orbitofrontal cortex was located ventral and rostral to the ventral premotor cortex.

RESULTS

Cortical projections to the SC were studied in five galagos. In three of these cases, injections involved only the superficial and intermediate layers (07–105, 07–111, 08–40), and in the other two cases injections involved superficial, intermediate, and deep layers (cases 09–34 and 09–03). Most injections included the upper visual quadrant and one case involved both the upper and lower visual fields. More superficial injections within the SC labeled neurons in visual areas of the occipital and temporal cortex, while injections involving deeper layers also labeled neurons in frontal and posterior parietal cortex. A summary of the number and percentage of labeled neurons from different cortical areas and regions to the SC is presented in Table 2.

Although it is difficult to determine the layers in which labeled neurons were located in the brain sections cut parallel to the cortical surface, the labeled cells were always found in the deeper sections for all cortical areas and were judged to be mainly or exclusively in infragranular layers below layer 4. In V1, layer 4 stains especially darkly for CO (Wong and Kaas, 2010) and was easily identified in our sections. Labeled cells were found in sections below layer 4.

Cases with injections into the superficial layers of the SC

In galago 07–111 (Fig. 3) an FR injection was placed in the SC representing the upper visual quadrant within 15–45° of paracentral vision. The injection site included the SZ, SGS, and SO layers of the SC (Fig. 2). Within V1, labeled neurons were mainly within the lateral part representing paracentral vision of the upper quadrant, matching the retinotopic location of the injection in the SC. There was no clear relation between the locations of labeled cells and cytochrome oxidase blob and interblob regions. The pattern of labeled neurons in rows in lateral V1 in Figure 3 is a consequence of imperfect flattening of V1 (area 17), as it was unfolded along its lateral margins. This resulted in individual sections moving between layers 4, without labeled cells, and 5, with labeled cells, multiple times along the extent of V1, and therefore creating the stripe-like patterns. As adjacent sections were processed for histology, the gaps in the distribution of labeled neurons in V1 were not filled in this reconstruction.

In V2, labeled cells were concentrated in a single patch located laterally and next to V3 where paracentral vision of the upper quadrant near the vertical meridian is represented. A scattering of labeled cells was found in lateral V3. Two patches of labeled cells in DM were observed and are consistent with the evidence that DM represents the upper as well as the lower visual quadrant (Lyon and Kaas, 2002). Surprisingly, no labeled cells were found in MT or MST, while many of labeled neurons were found in FST. A small number of labeled

cells were present in IT cortex ventral and rostral to FST. A few labeled cells were also present in posterior parietal cortex ventral to the IPS and between FST and auditory cortex. No labeled cells were found in somatosensory cortex, insular cortex, cingulate cortex, retrosplenial cortex, or (except for an occasional neuron) frontal cortex.

Similar results were obtained in galago 08–40 (Fig. 4). The injection site of this case was placed in the most caudal part of the medial SC, which represents peripheral vision of the upper visual quadrant (Lane et al., 1973). The injection involved the superficial layers of the SC, but was slightly deeper than the injection in case 07–111, and may have included the upper portion of the SGI. As expected from the location of this injection, labeled neurons were almost completely absent from portions of V1, V2, and V3 that represent central and even paracentral vision. The distributions of labeled cells within lateral V1, V2, and V3 were clearly in portions that represent the periphery of the upper visual field, and most of the label in medial V1 and V2 could be in parts that were unfolded from the calcarine sulcus when flattening cortex, and possibly in cortex that represents the upper visual quadrant (Rosa et al., 1997). Again, patches of labeled cells appeared in medial DM, suggesting that peripheral vision of the upper visual quadrant is represented medially in DM (Rosa et al., 1997; Allman and Kaas, 1975). Another possibility is that these cells are within area M (Allman and Kaas, 1976; Krubitzer and Kaas, 1993), which also has both upper and lower visual field representations. A few labeled neurons were in lateral DL (V4) or in cortex just lateral to DL. Only a few labeled cells were in MT, while dense patches of labeled cells were in FST and MST, providing evidence that peripheral vision is well represented in FST and MST. Other concentrations of labeled cells were in several locations across the temporal lobe including regions medial and rostral to MST and FST. These results suggest that peripheral vision is represented in several locations in the inferior temporal lobe. There were no foci of labeled neurons in visuomotor areas of posterior parietal cortex, motor and visuomotor areas of the frontal lobe, auditory cortex, or somatosensory cortex. These findings are consistent with previous evidence that projections of the superficial layers of the SC are from visual areas of cortex.

Our third case, 07–105, had CTB and FR injections into the superficial layers of the SC, with the FR injection being slightly more rostral than the CTB injection (Fig. 5B). The CTB injection was centered within the ventral portion of the SGS, but the tracer spread included the SZ, SGS, and the SO layers. The FR injection was slightly deeper within the SC with the injection core bordering the SO and ventral SGS, and the tracer spread including the SZ, SGS, SO, and the dorsal portion of the SGI layers.

For the most part, clusters of CTB and FR-labeled cells in cortex overlapped, with the distribution of FR-labeled neurons slightly closer to the representation of central vision within V1 than the distribution of CTB-labeled cells. Again, labeled cells were found in both lateral and medial V1 of the calcarine fissure. CTB and FR-labeled cells were found in lateral V2, with the distribution of FR cells slightly displaced medially toward central vision. The CTB cells were closer to the representation of the horizontal meridian along the estimated V2/V3 border. A small patch of FR cells lay rostral to the CTB cells within V3. Unexpectedly, a few CTB-labeled cells were present in dorsal V3 and in dorsal V2, while only FR cells were present in the location of DM. A few CTB-labeled cells were within MT, but no FR cells. The bulk of labeled cells within the MT complex were at the ventral junction with MST and dorsomedial FST. There was a high degree of overlap between the dense clusters of CTB and FR-labeled cells within dorsal FST, with the FR cells located more rostrally within FST than the CTB-labeled cells. Overlapping patches of FR and CTB-labeled cells were present within lateral DL. Few FR cells were located within IT, with one dense patch of cells just ventral to the estimated FST border, while CTB-labeled cells were found abundantly in IT with multiple clusters throughout the region. CTB and FR cells were

also located between auditory cortex and FST and MST, similar to case 08–40 (Fig. 4). There were a few cells within auditory cortex as well as cortex within the lateral sulcus. The deeper FR injection labeled a few cells within or medial to the frontal sulci (FS). No labeled cells were present within primary motor, ventral prefrontal cortex, or primary somatosensory cortex. A few labeled cells were within the region of the secondary somatosensory area and parietal ventral somatosensory (S2/PV) area.

Cases with injections into the deep layers of the SC

Case 09–34 had both CTB and FR injections into the SC. The injection cores were again within the SO, but the tracer spread for both tracers included the SZ, SGS, SO, SGI, and into the SAI, as well as a small portion ventrally within the SGP (Fig. 6E–H). The FR rostromedial injection was confined to the upper visual field representation. The more extensive CTB injection was largely caudal to the FR injection and included both upper and lower visual field representations within the SC. The pattern of labeled cells within early visual areas reflects the position of the FR and CTB injection sites with CTB-labeled cells in both upper and lower field representations within V1, V2, V3, and DL, while labeled cells were absent in the central vision representations. FR-labeled cells were found almost exclusively within upper field locations. Additionally, within the upper visual field representations of the early visual areas, the majority of FR-labeled cells were more medially located and closer to the representation of central vision than most of the CTB-labeled cells. Again, labeled cells formed lines within unfolded parts of striate cortex, and this is most likely due to uneven flattening. Consequently, the lines of cells observed in Figure 6 are a result of brain sections crossing cortex into and out of layer 5 two or more times. Most likely there are corticotectal projecting cells between these line formations, but they are probably in adjacent tissue sections processed for myelin, cytochrome oxidase, or in the alternate tracer sections. Unexpectedly, there was a patch of FR-labeled cells within dorsal V3 close to V2. This patch was medial and rostral to a patch of CTB-labeled cells in V3, but also caudal to another patch of CTB-labeled cells in DM. Additionally, there was another patch of CTB-labeled cells medial to the FR cells in dorsal V3. CTB-labeled cells medial to DM may be within the medial area (area M). Labeled cells were also found within the MT complex, with very few cells within MT itself. FR and CTB-labeled cells were found within caudal MST, as well as the dorsal half of FST. Similar to 07–105 (Fig. 5), the FR cells were more rostral than the CTB-labeled cells within FST. Another cluster, of two patches of both CTB and FR cells, was also present rostral to MTS. Multiple patches of labeled cells were located lateral to FST, again suggesting again the presence of multiple visual areas within IT cortex.

Unlike the cases with injections that are confined to the superficial layers, the deeper injections in this case labeled dense patches of cells within the posterior parietal cortex (PPC) and frontal cortex. Within PPC, the majority of labeled cells were located along the lateral lip of the interparietal sulcus (IPS). These patches spanned the length of the caudal half of the IPS, with branches of cells progressing medially into the IPS. A few more sparse patches of label were found medial to the IPS. In frontal cortex, the borders of FEF had been physiologically defined and lesions were placed along its borders (stars in Fig. 6A). Sparse distributions of both CTB and FR cells were present within the locations of the lesion sites, but the majority of labeled cells were located in cortex just ventral to the FEF (Fig. 6A). Multiple patches of label were located ventral and rostral to the frontal sulci extending into granular frontal cortex. Patches of labeled cells were also present within the medial wall, dorsal and rostral to the FEF. Only a few cells were in the region of S2/PV, and no cells were found within area 3b/S1 or motor cortex.

Case 09-03 had the deepest SC injection in our study. The CTB injection within the SC was centered in the SGI, but the tracer spread down to the periaqueductal gray (Fig. 7D). As in

the other cases, the majority of the injection core encompassed the representation of paracentral vision of the upper visual field. Retrogradely labeled cells were present within the upper field representations of V1, V2, V3, and DL. A dense patch of cells was also present within DM, with an additional dense patch of cells medial to DM, possibly within the medial area. The locations of MT, MST, and FST were estimated based on their expected locations relative to other visual areas and fissures, but it is likely that few if any cells were present within MT. By location, the majority of cells appear to be within FST. As in previous cases, multiple patches of labeled cells were within IT cortex, as well as rostral to MST, suggesting that multiple areas exist within these regions. A few labeled cells were present within the auditory core (Aud) as well as immediately caudal to the core in the expected region of the auditory belt. Other labeled cells were in the region of S2/PV. Similar to case 09–34 (Fig. 6) with injections into deep layers of the SC, dense patches of labeled cells were found just lateral to the IPS, although in case 09–03 the patches of labeled cells extended more rostrally. Patches of labeled cells were distributed rostrocaudally, just lateral to the IPS, with extensions of those patches extending medially toward the IPS. In frontal cortex, patches of labeled cells along the rostromedial aspect of the frontal sulcus may have included FEF, but the majority of cells were ventral as well as rostral to the expected location of FEF, in prefrontal cortex, and possibly into orbitofrontal cortex. The most caudal of the patches were likely in dorsal premotor cortex. The patches of label and the extents of labeled patches were more dense and expansive than in case 09–34 (Fig. 6). Patches of labeled cells were also present in polar frontal cortex of the medial wall and ventral surface. No cells were located within 3b/S1, and only a few were located within all of motor cortex.

In summary, superficial injections produced label in visual cortical areas such as V1, V2, V3, DM, FST, MST, and a small part of IT, with only a few cells present within MT. Deeper injections within the SC resulted in labeled cells within the posterior parietal cortex, S2/PV, auditory cortex, and frontal cortex, with relatively few cells originating from the FEF. No corticotectal projections were observed from primary somatosensory cortex, and only a few from motor cortex in any of our cases.

DISCUSSION

Prior to this study, most of what was known about corticotectal projections to the SC in prosimian galagos was obtained from separate studies with injections of tracers into three subdivisions of cortex, MT, DM, and S2/PV (Wall et al., 1982; Beck and Kaas, 1998a,b; Wu et al., 2005). In the present study, we determined the distribution of corticotectal projecting neurons from the whole cortex by making injections of retrograde tracers into the SC. Many of the connections observed in the present study were those expected from observations in other primate species (Fries, 1984, 1985; Cusick, 1988; Lock et al., 2003; Collins et al., 2005a,b), as there were dense projections from early visual areas to the superficial layers of the SC, while deeper layers of the SC received projections from visuomotor regions within frontal and parietal cortex. Unexpectedly, few neurons were labeled in MT after any of our SC injections. Dense projections from MT to the SC have been reported in New World and Old World monkeys (Graham et al., 1979; Maunsell and Van Essen, 1983; Ungerleider et al., 1984; Cusick, 1988; Lock et al., 2003; Collins et al., 2005a,b). Instead, we found that, in galagos, the majority of corticotectal projections from the MT complex come from FST, and others from MST (Fig. 3–Fig. 7). Another surprising observation was that there were relatively few projections from the FEF to the SC, although such connections appear to be dense in monkeys (Kunzle et al., 1976; Komatsu and Suzuki, 1985; Huerta et al., 1986; Stanton et al., 1988; Collins et al., 2005a,b).

Occipital cortex projections

Our results in prosimian primates are, for the most part, consistent with previous reports in monkeys: that dense, topographically organized inputs to the superficial layers of the SC originate from early visual areas (Wilson and Toyne, 1970; Tigges and Tigges 1981; Fries, 1984; Lock et al., 2003; Collins et al., 2005a,b). Yet, there were some deviations in our data relative to previous reports. For instance, in macaque monkeys corticotectal projections from striate cortex to the SC seem to correlate with cytochrome oxidase staining, with more cells originating from interblob regions than from within blobs (Lia and Olavarria, 1996). In V2, corticotectal projections originate from CO thick stripes (Abel et al., 1997). We did not find a correlation between CO interblobs and the location of labeled cells within striate cortex, and were unable to determine specific connection patterns within V2 because of the lack of CO stripe staining, as reported previously for V2 of galagos (Condo and Casagrande, 1990; Kaskan and Kaas, 2007; Wong and Kaas, 2010). The association between CO modules within V1 and V2 and their connections with the SC have not been studied in New World monkeys, so it is difficult to say whether connections specific to CO modules reflect a derived trait in all simians or just Old World monkeys.

Retrogradely labeled cells were present within DL (V4) in all studied cases. Most labeled cells were located within the caudal half of DL, much as in New World Monkeys (Cusick, 1988; Collins et al., 2005a,b). Rostral DL is thought to be involved in dorsal stream processing (Weller and Kaas, 1987; Cusick and Kaas, 1988; Kaas and Lyon, 2007).

Although labeled cells were present within DM (V3a) after superficial injections (Fig. 3), there were higher densities of labeled cells in this location after deeper injections (Fig. 6, Fig. 7). This is consistent with the results of Beck and Kaas (1998a,b) in galagos with DM injections, where terminal label was found within the SO and SGI and even some parts of the SGP. In owl monkeys, DM projects to the lower SGS (Graham et al., 1979).

Just medial to DM, area M (Allman and Kaas, 1976; Krubitzer and Kaas, 1993) contains a map of the complete contralateral visual field with equal amounts of cortex dedicated to central and peripheral vision. In our cases labeled cells were located in this region mainly after deep injections (Fig. 4, Fig. 6, Fig. 7). Not much is known about area M, other than it shares connections with V2, DM, areas rostral to MT, and the posterior parietal cortex (Graham et al., 1979; Krubitzer and Kaas, 1993). Area PO of macaques likely corresponds to area M, as PO has connections with posterior parietal cortex, and frontal cortex, as well as occipital visual areas (Colby et al., 1988). Cortex in the PO region has also been called V6 (Shipp et al., 1998).

MT complex projections

Previous reports have suggested strong connections between MT and SC in New World and Old World monkeys (Graham et al., 1979; Fries, 1984; Lock et al., 2003; Collins et al., 2005a,b) and even connections between MT and the SC in galagos (Wall et al., 1982). However, the injections by Wall et al. (1982) could have involved surrounding areas such as MST, FST, and MTc, particularly since FST appears to project densely to the SC in galagos. Alternatively, it could be that parts of FST and MST in our present figures are actually part of MT, but that seems unlikely, since most of the label attributed to FST and MST was outside of the architectural borders of MT. Because the lack of evidence for MT projections to the SC was surprising, we examined previously published galago cases with MT injections from our laboratory (Wong et al., 2009). Of four cases (07–45, 98–101, 05–40, 06–58 from Wong et al., 2009) with anterograde label in the thalamus and brainstem, we found only one case that had any detectable terminal label within the SC. The terminal label was very weak within the SGS of the SC, but it was in the expected location given the

topography of both MT and the SC. Given these observations in the present study, and the unpublished data from our previous study, we conclude that the lack of labeled cells within MT after SC injections reflects a sparseness of projections to the SC in galagos, and that corticotectal projections from this region of cortex derive mainly from FST, with some from MST. MT also has few connections with FEF in New World monkeys (Weller and Kaas, 1984; Huerta et al., 1987; Krubitzer and Kaas, 1990; Rosa et al., 1993; Tian et al., 1996), and prosimian galagos (Krubitzer and Kaas, 1990; Stepniewska et al., 2009), while studies of connections between MT and FEF in Old World macaque monkeys have produced variable results, with some studies reporting sparse or no connections (Maunsell and Van Essen, 1983; Ungerleider and Desimone, 1986), yet others provided evidence for such connections (Andersen et al., 1985; Huerta et al., 1987; Schall et al., 1995). The variability of the connections of MT with FEF and the SC across primate taxa suggests that MT, an area that may have evolved with primates (Kaas, 2003), has an evolving role in vision, and that an involvement in the production of saccadic eye movements via the SC and FEF connections fully emerged in catarrhine primates.

The majority of labeled cells in FST were within the dorsal half, usually close to the MT border. Although we did not differentiate between FSTd and FSTv (Kaas and Morel, 1993), the majority of corticotectal projections were in dorsal FST. FSTd has connections with MT (Kaas and Morel, 1993), and thus MT could indirectly influence the SC via a relay through FST. In macaques, connections between FST and the SC have been reported (Lock et al., 2003). In New World monkeys, the corticotectal projections arise from the most dorsal portion of FST (Collins et al., 2005a,b), as in galagos. Labeled cells were also found in MST. This area is thought to be involved in higher order visual motion processing, such as expansion, contraction and rotation, optic flow, object motion, and even smooth pursuit eye movements (Komatsu and Wurtz, 1988; Tanaka and Saito, 1989; Britten and van Wezel, 1998). In galagos, MST also has relatively strong connections with portions of the posterior parietal cortex where defensive movements of the face and forelimb can be evoked by electrical stimulation (Stepniewska et al., 2009). MST in New World and Old World monkeys also has connections with the FEF (Huerta et al., 1987). We found few cells within MTc/V4t after SC injections, yet there is some evidence for such connections from V4t of macaques (Lock et al., 2003).

Inferior temporal cortex projections

After injections in the SC of galagos, multiple patches of retrogradely labeled cells were observed within the inferior temporal (IT) cortex (Fig. 3, Fig. 5–Fig. 7). While we did not identify divisions within IT cortex in the present cases, architectonic subdivisions of the temporal lobe in galagos have been proposed (Zilles, 1979; Preuss and Goldman-Rakic, 1991a; Wong et al., 2010). The presence of multiple patches of labeled cells in IT cortex is consistent with the architectonic evidence that several functional divisions exist in this region. The significance of IT projections to the SC in Old World macaque monkeys is uncertain, as one study (Fries 1984) provided evidence for strong connections between IT cortex and the SC, while another study (Lock et al., 2003) showed rather weak corticotectal projections from this region. Additionally, few projections from IT cortex have been observed in New World monkeys (Collins et al., 2005a,b). Because of the differences in these results, it is difficult to reconstruct the ancestral pattern present in early primates and more studies are needed.

Posterior parietal cortex projections

In the present study, deep injections in the SC labeled large population of neurons in a rostrocaudal band of posterior parietal cortex, just lateral to the intraparietal sulcus. The organization of this region of cortex in galagos is not well understood, but the rostral half of

this population of labeled neurons lies in a region where electrical stimulation with microelectrodes evokes ear movements, eye lid closure, and face defensive movements (Stepniewska et al., 2005, 2009a). Some of this movement-producing cortex has connections with MST and other visual areas but not MT (Stepniewska et al., 2009b). MT connections appear to be more caudal in posterior parietal cortex (Wall et al., 1982; Kaskan and Kaas, 2007), overlapping the caudal part of the band of SC projecting cells, where electrical stimulation failed to produce eye or arm movements (Stepniewska et al., 2009a). This unresponsive region in the caudal half of posterior parietal cortex has strong connections to visual areas of occipital cortex (Stepniewska et al., 2009a). The posterior parietal cortex has been subdivided architectonically by Preuss and Goldman-Rakic (1991a) and homologies with subdivisions of area 7 of macaque have been suggested, but supportive evidence is limited. In macaques, eye movements have been evoked by electrical stimulation of the lateral intraparietal area, LIP, and eye blinking has been evoked from sites just rostral to those that produced saccades (Shibutani et al., 1984; Their and Andersen, 1998). The resulting actions from electrical stimulation of LIP and rostrally adjoining cortex in macaques seem very similar to the eye movements and more rostral eye lid closure zones of posterior parietal cortex in galagos (which are lateral to the intraparietal sulcus), but cortical connections appear to differ. While the movement zones in galagos do not appear to receive inputs from MT and DM (V3a), such inputs to LIP have been reported for macaques (Cavada and Goldman-Rakic, 1989; Blatt et al., 1990; Nakamura et al., 2001); however, Maunsell and Van Essen (1983) used connections with MT to define the ventral intraparietal area VIP, not LIP. The cortex, just lateral to the intraparietal sulcus, in galagos projects densely to the deep layers of the SC, as does LIP in macaques (Lynch et al., 1985; Pare and Wurtz, 1997; Lock et al., 2003). Overall, the evidence suggests that a homolog of LIP exists in galagos just lateral to a rostral portion of the intraparietal sulcus. In macaques, and possibly New World monkeys, the region of LIP projects to the FEF (Barbas and Mesulam, 1981; Andersen et al., 1985; Huerta et al., 1987), but this is uncertain in galagos (Fang et al., 2005). In macaques, face, eye, and arm defensive movements have been attributed to the ventral intraparietal area, VIP (Cooke et al., 2003), and eye, ear, and face defensive movements can be evoked from the rostral part of the zone with dense projections to the SC in galagos. While the SC is not usually associated with defensive movements, such movements have been reported after SC stimulation in rats (see Schenberg et al., 2005, for review).

After injections of tracer into posterior parietal cortex of New World monkeys, Graham et al. (1979) described projections to the lower layers of the SGS of the SC. However, Collins et al. (2005a,b) found few labeled neurons in posterior parietal cortex of New World monkeys after injections in the SC. Our present results, together with those of Graham et al. (1979), suggest that the SC injections made by Collins et al. (2005a,b) may have been too superficial to label neurons in posterior parietal cortex. Thus, projections from posterior parietal cortex to the SC are most likely part of a visuomotor network shared by all primates.

Frontal cortex projections

Few, if any, labeled cells were present in frontal cortex after superficial injections into the SC (Fig. 3–Fig. 5). However, after deep injections we found cells within frontal cortex, rostral to the caudal half of the frontal sulci (Fig. 6, Fig. 7). Surprisingly we found few cells within FEF in the case where we used microstimulation to define the boundaries of FEF (Fig. 6), and few cells were present in the expected location of FEF, just medial to the rostral end of the frontal sulcus (see Fang et al., 2005, for another galago where the FEF was identified by microstimulation), in the other case with labeled cells in frontal cortex (Fig. 7). A lack of FEF projections to the SC in galagos has also been reported after FEF injections (Stepniewska et al., 2009c). In most other primates where SC projections have been studied,

reports clearly indicate a strong FEF input to the SC (Ku'nzle et al., 1976; Fries 1984, 1985; Komatsu and Suzuki, 1985; Huerta et al., 1986; Stanton et al., 1988; Collins et al., 2005a,b). Thus, the lack of evidence for such projections in galagos is surprising. As eye movements can be evoked by electrical stimulation of FEF in galagos, the eye movement may depend on direct projections to brainstem oculomotor neuron pools, rather than by projections to the SC.

While there were few projections to the SC from FEF in galagos, there were strong projections within the regions of the dorsal and ventral premotor cortex and granular frontal cortex. Only a few labeled cells were observed in orbitofrontal cortex after our deepest SC injections (Fig. 7) and these cells could be a result of our injection site spreading into the periaqueductal gray (Leichnetz et al., 1981). When relating the position of our labeled cells in frontal cortex to the motor maps described in Wu et al. (2000), it is likely that the dense patch of labeled cells ventral to FEF along the rostral end of the frontal sulcus could be within a region where ear movements are elicited. The labeled neurons could also be in a region of cortex just ventral to the FEF that has connections with MT in New World monkeys (Krubitzer and Kaas, 1990). Marmosets have cells projecting to the SC that are located outside of FEF in the ventral and dorsal premotor areas as well as granular cortex (fig. 2. of Collins et al., 2005a,b). Yet, few such cells were identified outside of the FEF in titi and owl monkeys. The lack of cells outside of FEF for these cases is, perhaps, a result of injection sites being limited to the depth of the SGI.

After deep injections into macaque SC, cells dorsal and anterior to FEF including both areas 6 and 8, as well as cells within the medial wall were labeled (Fries, 1985; Pouget et al., 2009). Goldman and Nauta (1976) described projections from the middle third of the length of the dorsal bank of the principal sulcus to intermediate and deeper layers of the SC. Leichnetz et al. (1981) suggested that the distribution of prefrontal projections to the SC was extensive in both New World cebus and Old World macaque monkeys, with cortex rostral to the arcuate sulcus projecting to the SC, including cortex of the dorsal bank of the principal sulcus, but not the orbitofrontal cortex. Projections from dorsolateral prefrontal cortex to the SC may be involved in transmitting information on visuospatial working memory and task-selective signals (Johnston and Everling, 2006, 2009).

Auditory cortex projections

In galagos, only a few labeled cells were found within auditory cortex after deep SC injections. The location of cells in auditory cortex were likely in both core and belt regions of the auditory cortex. In four cases, labeled cells were present in a dense cluster rostral to MST (Fig. 4 –Fig. 7), which coincides with the temporoparietal area (Tpt), a higher-order auditory area that has strong connections with frontal cortex (Preuss and Goldman-Rakic, 1991b) and connections with regions of posterior parietal cortex where defensive behaviors are evoked by electrical stimulation (Stepniewska et al., 2009, fig. 3, fig. 6, 10, 11).

In New World and Old World primates, the deep layers of the SC contain cells that are responsive to auditory stimuli (Jay and Sparks, 1987; Wallace et al., 1996). The majority of auditory inputs to the SC are likely from sub-cortical structures, as only sparse if any corticotectal projections have been reported from primary auditory cortex in New and Old World monkeys (Fries, 1984; Collins et al., 2005a,b). However, multisensory cortex between auditory and visual sensory areas may be a source of auditory inputs (Stein et al., 2004).

Somatosensory cortex

In the present cases no labeled cells were found in primary somatosensory cortex, but some cells were present within the S2/PV region after deep injections into the SC. This is consistent with previous reports of terminal label within the SGI and SGP layers of the SC after anatomical tracer injections into S2/PV of galago cortex (Wu et al., 2005), and results from several studies suggesting that primary somatosensory cortex does not project to the SC (Fries, 1984; Wu et al., 2005; Collins et al., 2005a,b). Projections from PV/S2 to the SC were sparse in New World monkeys (Collins et al., 2005a,b, fig. 2), but the injection depths were relatively superficial within the SC and often did not include lower portions of the SGI or the SGP. Fries (1984) described a weak projection from the region of S2/PV in macaque monkeys, while Lock (2003) did not mention such connections. An orderly somatosensory map is present within the intermediate layers of the SC (Updyke, 1974; Stein, 1976). The majority of somatosensory input to the SC is thought to arise from subcortical structures such as the cuneate and gracile nuclei along with a few inputs from the spinal cord (Wiberg et al., 1987). However, some somatosensory information reaches the SC from cortex via S2/PV. Wu et al. (2005) suggest that these inputs may not function to guide orienting movements or contribute to the somatotopic representation within the deep layers of the SC, as inputs from tracer injections localized to a single body structure, such as the face, covered most of the extent of the SC in galagos. Thus, the projections do not appear to provide somatotopically precise information.

CONCLUSIONS

While an optic tectum or SC is common to all vertebrates, the connections and functions of this structure appear to vary. In all studied mammals, areas of neocortex project to the SC, where they influence tectal projections to brainstem motor centers and the visual thalamus. Here we provide evidence that early visual areas, V1, V2, and V3, project to the superficial layers of the SC of galagos as they do in other primates. However, we were surprised by the evidence that two cortical areas that project densely to the SC in New and Old World monkeys, MT and FEF, do not appear to do so in galagos. The reasons for these differences are unclear. Although these areas appear to have evolved with primates (Kaas, 2002), they may vary in connections and functions across primate taxa. In cortical regions where cortical areas have been less well defined, differences and similarities across species are less certain. For example, a portion of posterior parietal cortex in both galagos and monkeys project densely to the SC, but homologs of cortical areas in these two groups remain uncertain. Yet some features of the projection zone in galagos suggest that this zone contains homologs of LIP and VIP of macaques.

Acknowledgments

We thank Laura Trice for help with histological procedures, Mary Feurtado and Christine Collins for surgical assistance, Iwona Stepniewska for assistance in microstimulation procedures and helpful comments on the article, and Pooja Balam for helpful comments on the article. We also thank Peiyan Wong for access to tissue and data from a galago experiment.

Grant sponsor: National Eye Institute; Grant numbers: RO1 EY-02686 (to J.H.K.) and CORE grants P30 EY-008126.

LITERATURE CITED

Abel PL, O'Brien BJ, Lia B, Olavarria JF. Distribution of neurons projecting to the superior colliculus correlates with thick cytochrome oxidase stripes in macaque visual area V2. *J Comp Neurol.* 1997; 377:313–323. [PubMed: 8989648]

- Allman JM, Kaas JH. The organization of the second visual area (VII) in the owl monkey: a second order transformation of the visual hemifield. *Brain Res.* 1974; 76:247–265. [PubMed: 4210762]
- Allman JM, Kaas JH. The dorsomedial cortical visual area: a third tier area in the occipital lobe of the owl monkey (*Aotus trivirgatus*). *Brain Res.* 1975; 100:473–487. [PubMed: 811327]
- Allman JM, Kaas JH. Representation of the visual field on the medial wall of the occipital-parietal cortex in the owl monkey. *Science.* 1976; 191:572–575. [PubMed: 814619]
- Allman JM, Kaas JH, Lane RH. The middle temporal visual area (MT) in the bushbaby, *Galago senegalensis*. *Brain Res.* 1973; 57:197–202. [PubMed: 4197774]
- Andersen RA, Asanuma C, Cowan WM. Callosal and prefrontal associational projecting cell populations in area 7A of macaque monkey: A study using retrogradely transported fluorescent dyes. *J Comp Neurol.* 1985; 232:443–455. [PubMed: 3980763]
- Balaram P, Takahata T, Kaas JH. VGLUT2 mRNA and protein expression in the visual thalamus and midbrain of prosimian galagos (*Otolemur garnetti*). *Eye and Brain.* 2011; 3:5–15. [PubMed: 22984342]
- Baldwin MKL, Wong P, Reed JL, Kaas JH. Superior colliculus connections with visual thalamus in gray squirrels (*Sciurus carolinensis*): evidence for four subdivisions within the pulvinar complex. *J Comp Neurol.* 519:1071–1094. [PubMed: 21344403]
- Barbas H, Mesulam MM. Organization of afferent input to subdivisions of area 8 in the rhesus monkey. *J Comp Neurol.* 1981; 200:407–431. [PubMed: 7276245]
- Beck PD, Kaas JH. Thalamic connections of the dorsomedial visual area in primates. *J Comp Neurol.* 1998a; 396:381–398. [PubMed: 9624591]
- Beck PD, Kaas JH. Cortical connections of the dorsomedial visual area in prosimian primates. *J Comp Neurol.* 1998b; 398:162–178.
- Blatt GJ, Andersen RA, Stoner GR. Visual receptive field organization and cortico-cortical connections of the lateral intraparietal area (area LIP) in the macaque. *J Comp Neurol.* 1990; 299:421–445. [PubMed: 2243159]
- Britten KH, van Wezel RJ. Electrical microstimulation of cortical area MST biases heading perception in monkeys. *Nat Neurosci.* 1998; 1:59–63. [PubMed: 10195110]
- Brugge, JF. Auditory cortical areas in primates. In: Woolsey, CN., editor. *Cortical sensory organization*. Vol. 3. New York: Raven Press; 1981. p. 97–111. Multiple auditory areas
- Cavada C, Goldman-Rakic PS. Posterior parietal cortex in rhesus monkey. I. Parcellation of areas based on distinctive limbic and sensory corticocortical connections. *J Comp Neurol.* 1989; 287:393–421. [PubMed: 2477405]
- Colby CL, Gattass R, Olson CR, Gross CG. Topographical organization of cortical afferents to extrastriate visual area PO in the macaque: a dual tracer study. *J Comp Neurol.* 1988; 269:392–413. [PubMed: 2453534]
- Collins CE, Stepniewska I, Kaas JH. Topographic patterns of v2 cortical connections in a prosimian primate (*Galago garnetti*). *J Comp Neurol.* 2001; 431:155–167. [PubMed: 11169997]
- Collins CE, Xu X, Khaytin I, Kaskan PM, Casagrande VA, Kaas JH. Optical imaging of visually evoked responses in the middle temporal area after deactivation of primary visual cortex in adult primates. *Proc Natl Acad Sci U S A.* 2005a; 102:5594–5599. [PubMed: 15809438]
- Collins CE, Lyon DC, Kaas JH. Distribution across cortical areas of neurons projecting to the superior colliculus in New World monkeys. *Anat Rec Part A.* 2005b; 285A:619–627.
- Condo GJ, Casagrande VA. Organization of cytochrome oxidase dense staining in the visual cortex of nocturnal primates (*Galago crassicaudatus* and *Galago senegalensis*): I, adult patterns. *J Comp Neurol.* 1990; 293:632–645. [PubMed: 2158503]
- Cooke DF, Taylor CS, Moore T, Graziano MS. Complex movements evoked by microstimulation of the ventral intraparietal area. *Proc Natl Acad Sci U S A.* 2003; 100:6163–6168. [PubMed: 12719522]
- Cowey A, Perry VH. The projection of the fovea to the superior colliculus in rhesus monkeys. *Neuroscience.* 1980; 5:53–61. [PubMed: 6768002]
- Cusick CG. Anatomical organization of the superior colliculus in monkeys: corticotectal pathways for visual and visuomotor functions. *Prog Brain Res.* 1988; 75:1–15. [PubMed: 2847239]

- Cusick CG, Kaas JH. Cortical connections of area 18 and dorsolateral visual cortex in squirrel monkeys. *Vis Neurosci*. 1988; 1:211–237. [PubMed: 2484948]
- Fang PC, Stepniewska I, Kaas JH. Ipsilateral cortical connections of motor, premotor, frontal eye, and posterior parietal fields in prosimian primate, *Otolemur garnetti*. *J Comp Neurol*. 2005; 490:305–333. [PubMed: 16082679]
- Fitzpatrick D, Carey RG, Diamond IT. Projections of the superior colliculus upon the lateral geniculate body in tupaia glis and galago senegalensis. *Brain Res*. 1980; 194:494–499. [PubMed: 7388626]
- Fries W. Cortical projections to the superior colliculus in the macaque monkey: a retrograde study using horseradish peroxidase. *J Comp Neurol*. 1984; 230:55–76. [PubMed: 6096414]
- Fries W. Inputs from motor and premotor cortex to the superior colliculus of the macaque monkey. *Behav Brain Res*. 1985; 18:95–105. [PubMed: 3913446]
- Gallyas F. Silver staining of myelin by means of physical development. *Neurol Res*. 1979; 1:203–209. [PubMed: 95356]
- Geneser-Jensen FA, Blackstad TW. Distribution of acetylcholinesterase in the hippocampal region of the guinea pig. I. Entorhinal area, parasubiculum, and presubiculum. *Z Zellforsch Mikrosk Anat*. 1971; 114:460–481. [PubMed: 5550728]
- Goldman PS, Nauta WJH. Autoradiographic demonstration of a projection from prefrontal association cortex to the superior colliculus in the rhesus monkey. *Brain Res*. 1976; 116:145–149. [PubMed: 824019]
- Graham J, Lin CS, Kaas JH. Subcortical projections of six visual cortical areas in the owl monkey, *Aotus trivirgatus*. *J Comp Neurol*. 1979; 187:557–580. [PubMed: 114555]
- Huerta MT, Krubitzer LA, Kaas JH. Frontal eye field as defined by intracortical microstimulation in squirrel monkeys, owl monkeys, and macaque monkeys. I. Subcortical connections. *J Comp Neurol*. 1986; 253:415–439. [PubMed: 3793998]
- Huerta MF, Krubitzer LA, Kaas JH. Frontal eye field as defined by intracortical microstimulation in squirrel monkeys, owl monkeys, and macaque monkeys. II. Cortical connections. *J Comp Neurol*. 1987; 265:332–361. [PubMed: 2447132]
- Jay MF, Sparks DL. Sensorimotor integration in the primate superior colliculus. II. Coordinates of auditory signals. *J Neurophysiol*. 1987; 57:35–55.
- Jerison, HV. What fossils tell us about the evolution of neocortex. In: Kaas, JH.; Krubitzer, LA., editors. *Evolution of nervous systems*. Vol. vol 3. Mammals. London: Elsevier; 2007. p. 1-12.
- Johnston K, Everling S. Monkey dorsolateral prefrontal cortex sends task-selective signals directly to the superior colliculus. *J Neurosci*. 2006; 26:12471–12478. [PubMed: 17135409]
- Johnston K, Everling S. Task-relevant output signals are sent from monkey dorsolateral prefrontal cortex to the superior colliculus during a visuospatial working memory task. *J Cogn Neurosci*. 2009; 21:1023–1038. [PubMed: 18702590]
- Kaas JH. Convergences in the modular and areal organization of the forebrain of mammals: implications for the reconstruction of forebrain evolution. *Brain Behav Evol*. 2002; 59:262–272. [PubMed: 12207083]
- Kaas, JH. The evolution of the visual system in primates. In: Chalupa, L.; Werner, JD., editors. *The visual neurosciences*. Cambridge, MA: MIT Press; 2003. p. 1563-1572.
- Kaas JH, Huerta MF. The subcortical visual system of primates. In: *Comparative primate biology*. 1988; vol. 4:327–391. Neurosciences.
- Kaas JH, Lyon DC. Pulvinar contributions to the dorsal and ventral streams of visual processing in primates. *Brain Res Rev*. 2007; 55:285–296. [PubMed: 17433837]
- Kaas JH, Morel A. Connections of visual areas of the upper temporal lobe of owl monkeys: the MT crescent and dorsal and ventral subdivisions of FST. *J Neurosci*. 1993; 13:534–546. [PubMed: 8381166]
- Kaskan PM, Kaas JH. Cortical connections of the middle temporal and the middle temporal crescent visual areas in prosimian galagos (*Otolemur garnetti*). *Anat Rec (Hoboken)*. 2007; 290:349–366. [PubMed: 17525950]
- Komatsu H, Suzuki H. Projections from the functional subdivisions of the frontal eye field to the superior colliculus in monkey. *Brain Res*. 1985; 327:324–327. [PubMed: 2985177]

- Komatsu H, Wurtz RH. Relation of cortical areas MT and MST to pursuit eye movements. III. Interaction with full field visual stimulation. *J Neurophysiol.* 1988; 60:621–644. [PubMed: 3171645]
- Krubitzer LA, Kaas JH. Cortical connections of MT in four species of primates: areal, modular, and retinotopic patterns. *Vis Neurosci.* 1990; 5:165–204. [PubMed: 2278944]
- Krubitzer LA, Kaas JH. The somatosensory thalamus of monkeys: cortical connections and a redefinition of nuclei in marmosets. *J Comp Neurol.* 1992; 319:123–140. [PubMed: 1375605]
- Krubitzer LA, Kaas JH. The dorsomedial visual area of owl monkeys: connections, myeloarchitecture, and homologies in other primates. *J Comp Neurol.* 1993; 334:497–528. [PubMed: 8408763]
- Ku'nzle H, Akert K, Wurtz RH. Projection of area 8 (frontal eye field) to superior colliculus in the monkey. An autoradiographic study. *Brain Res.* 1976; 117:487–492. [PubMed: 825196]
- Lane RH, Allman JM, Kaas JH, Miezin FM. The visuotopic organization of the superior colliculus of owl monkey (*Aotus trivirgatus*) and the bush baby (*Galago senegalensis*). *Brain Res.* 1973; 60:335–349. [PubMed: 4202853]
- Le Gros Clark WE. The brain of microcebus murinus. *Proc Zool Soc Lond.* 1931; 101:463–486.
- Leichnetz GR, Spencer RF, Hardy SGP, Astruc J. The prefrontal corticotectal projection in the monkey: an anterograde and retrograde horseradish peroxidase study. *Neuroscience.* 1981; 6:1023–1041. [PubMed: 6168970]
- Lia B, Olavarria JF. The distribution of cortical projection neurons correlates with the interblob compartment in macaque striate cortex. *Vis Neurosci.* 1996; 13:461–466. [PubMed: 8782373]
- Lock TM, Baizer JS, Bender DB. Distribution of corticotectal cells in macaque. *Exp Brain Res.* 2003; 151:455–470. [PubMed: 12851806]
- Lyon DC, Kaas JH. Connectional evidence for dorsal and ventral V3, and other extrastriate areas in prosimian primate, *Galago garnetti*. *Brain Behav Evol.* 2002; 59:114–129. [PubMed: 12119531]
- Lynch JC, Graybiel AM, Lobeck LJ. The differential projection of two cytoarchitectonic subregions of the inferior parietal lobule of macaque upon the deep layers of the superior colliculus. *J Comp Neurol.* 1985; 235:241–254. [PubMed: 3998211]
- Lynch JC, Hoover JE, Strick PL. Input to the primate frontal eye field from the substantia nigra, superior colliculus, and dentate nucleus demonstrated by transneuronal transport. *Exp Brain Res.* 1994; 100:181–186. [PubMed: 7813649]
- Martin, RD. Primate origins and evolution. London: Chapman and Hall; 1990.
- Maunsell JH, Van Essen DC. The connections of the middle temporal visual area (MT) and their relationship to a cortical hierarchy in the macaque monkey. *J Neurosci.* 1983; 3:2563–2596. [PubMed: 6655500]
- May PJ. The mammalian superior colliculus: laminar structure and connections. *Prog Brain Res.* 2006; 151:321–378. [PubMed: 16221594]
- Nakamura H, Kuroda T, Wakita M, Kusunoki M, Kato A, Mikami A, Sakata H, Itoh K. From three-dimensional space vision to prehensile hand movements: the lateral intraparietal area links the area V3A and the anterior intraparietal area in macaques. *J Neurosci.* 2001; 15:8174–8187. [PubMed: 11588190]
- Pare M, Wurtz RH. Monkey posterior parietal cortex neurons antidromatically activated from superior colliculus. *J Neurophysiol.* 1997; 78:3493–3497. [PubMed: 9405568]
- Pouget P, Stepniewska I, Crowder EA, Leslie MW, Emeric EE, Nelson M, Schall JD. Visual and motor connectivity and the distribution of calcium-binding proteins in macaque frontal eye field: implications for saccade target selection. *Front Neuroanat.* 2009; 3:2. [PubMed: 19506705]
- Preuss TM, Goldman-Rakic PS. Architectonics of the parietal and temporal association cortex in the strepsirhine primate *galago* compared to the anthropoid primate *macaca*. *J Comp Neurol.* 1991a; 310:475–506. [PubMed: 1939733]
- Preuss TM, Goldman-Rakic PS. Ipsilateral cortical connections of granular frontal cortex in the strepsirhine primate *galago*, with comparative comments on anthropoid primates. *J Comp Neurol.* 1991b; 310:507–549. [PubMed: 1719039]
- Rhoades RW, Chalupa LM. Functional properties of the corticotectal projection in the golden hamster. *J Comp Neurol.* 1978; 180:617–634. [PubMed: 659676]

- Rosa MG, Soares JG, Fiorani M Jr, Gattas R. Cortical afferents of visual area MT in the Cebus monkey: possible homologies between New and Old World monkeys. *Vis Neurosci.* 1993; 10:827–855. [PubMed: 8217935]
- Rosa MG, Casagrande VA, Preuss T, Kaas JH. Visual field representation in striate and prestriate cortices of a prosimian primate (*Galago garnetti*). *J Neurophysiol.* 1997; 77:3193–3217. [PubMed: 9212268]
- Schall JD, Morel A, King DJ, Bullier J. Topography of visual cortex connections with frontal eye field in macaque: convergence and segregation of processing streams. *J Neurosci.* 1995; 15:4464–4487. [PubMed: 7540675]
- Schenberg LC, Povaia RM, Costa AL, Caldellas AV, Tufik S, Bittencourt AS. Functional specializations within the tectum defense systems of the rat. *Neurosci Biobehav Rev.* 2005; 29:1279–1298. [PubMed: 16087233]
- Shibutani H, Sakata H, Hyvarinen J. Saccade and blinking evoked by microstimulation of the posterior parietal association cortex of the monkey. *Exp Brain Res.* 1984; 55:1–8. [PubMed: 6745342]
- Shipp S, Blanton M, Zeki S. A visuo-somatomotor pathway through superior parietal cortex in the macaque monkey: cortical connections of area V6 and V6A. *Eur J Neurosci.* 1998; 10:3171–3193. [PubMed: 9786211]
- Smith EG. On the morphology of the brain in the Mammalia, with special reference to that of the lemurs, recent and extinct. *Trans Linnean Soc Lond.* 1903; 8:319–432.
- Stanton GB, Goldberg ME, Bruce CJ. Frontal eye field efferents in the macaque monkey. II. Topography of terminal fields in midbrain and pons. *J Comp Neurol.* 1988; 271:493–506. [PubMed: 2454971]
- Stein BE, Magalhaes-Castro B, Kruger L. Relationship between visual and tactile representations in cat superior colliculus. *J Neurophysiol.* 1976; 39:401–419. [PubMed: 1255230]
- Stein Be Jiang, W.; Staford, TR. Multisensory integration in single neurons of the midbrain. In: Calvert, G.; Spence, C.; Stein, BE., editors. *The handbook of multisensory processes*. Cambridge, MA: MIT Press; 2004. p. 243–264.
- Stephan H, Frahm H, Baron G. New and revised data on volumes of brain structures in insectivores and primates. *Folia Prim.* 1981; 35:1–29.
- Stepniewska I, Fang PC, Kaas JH. Microstimulation reveals specialized subregions of different complex movements in posterior parietal cortex of prosimian galagos. *Proc Natl Acad Sci U S A.* 2005; 102:4878–4883. [PubMed: 15772167]
- Stepniewska I, Fang PC, Kaas JH. Organization of the posterior parietal cortex in galagos. I. Functional zones identified by microstimulation. *J Comp Neurol.* 2009a; 517:765–782. [PubMed: 19852065]
- Stepniewska I, Cerkevich CM, Fang PC, Kaas JH. Organization of the posterior parietal cortex in galagos. II. Ipsilateral cortical connections of physiologically identified zones within interior sensorimotor region. *J Comp Neurol.* 2009b; 517:783–807. [PubMed: 19844952]
- Stepniewska I, Pouget P, Baldwin MKL, Kaas JH. Cortical and subcortical connections of the frontal eye field in prosimian primates. *Soc Neurosci Abstr.* 2009c; 263:10. Y27.
- Symonds LL, Kaas JH. Connections of striate cortex in prosimian, galago senegalensis. *J Comp Neurol.* 1978; 181:477–512. [PubMed: 690275]
- Tanaka K, Saito H. Analysis of motion of the visual field by direction, expansion/contraction, and rotation cells clustered in the dorsal part of the medial superior temporal area of the macaque monkey. *J Neurophysiol.* 1989; 62:626–641. [PubMed: 2769351]
- Their P, Andersen RA. Electrical microstimulation distinguishes distinct saccade-related areas in the posterior parietal cortex. *J Neurophysiol.* 1998; 80:1713–1735. [PubMed: 9772234]
- Tian JR, Lynch JC. Corticocortical input to the smooth and saccadic eye movement subregions of the frontal eye field in cebus monkeys. *J Neurophysiol.* 1996; 76:2754–2771. [PubMed: 8899643]
- Tigges J, Tigges M. Distribution of retinofugal and corticofugal axon terminals in the superior colliculus of squirrel monkey. *Inv Ophthalmol Vis Sci.* 1981; 20:149–158.
- Tootell RB, Hamilton SL, Silberman MS. Topography of cytochrome oxidase activity in owl monkey cortex. *J Neurosci.* 1985; 5:2786–2800. [PubMed: 2995611]

- Ungerleider LG, Desimone R. Cortical connections of the visual area MT in the macaque. *J Comp Neurol.* 1986; 248:190–222. [PubMed: 3722458]
- Ungerleider LG, Desimone R, Galkin TW, Mishkin M. Subcortical projections of area MT in macaque. *J Comp Neurol.* 1984; 223:368–386. [PubMed: 6323553]
- Updyke BV. Characteristics of unit responses in superior colliculus of the cebus monkey. *J Neurophysiol.* 1974; 37:896–909. [PubMed: 4212987]
- Wall JT, Symonds LL, Kaas JH. Cortical and subcortical projections of the middle temporal area (MT) and adjacent cortex in galagos. *J Comp Neurol.* 1982; 211:193–214. [PubMed: 7174890]
- Wallace MT, Wilkinson LK, Stein BE. Representation and integration of multiple sensory inputs in primate superior colliculus. *J Neurophysiol.* 1996; 76:1246–1266. [PubMed: 8871234]
- Weller RE, Kaas JH. Subdivisions and connections of the inferior temporal cortex in owl monkeys. *J Comp Neurol.* 1987; 256:137–172. [PubMed: 3819036]
- Weller RE, Wall JT, Kaas JH. Cortical connections of the middle temporal visual area (MT) and the superior temporal cortex in owl monkeys. *J Comp Neurol.* 1984; 228:81–104. [PubMed: 6480909]
- Wiberg M, Westman J, Blomqvist A. Somatosensory projections to the mesencephalon: an anatomical study in the monkey. *J Comp Neurol.* 264:92–117. [PubMed: 2445793]
- Wilson ME, Toyne MJ. Retino-tectal and cortico-tectal projections in *Macaca mulatta*. *Brain Res.* 1970; 24:395–406. [PubMed: 4099749]
- Wong P, Kaas JH. Architectonic subdivisions of neocortex in the galago (*Otolemur garnetti*). *Anat Rec.* 2010; 293:1033–1069.
- Wong P, Collins CE, Baldwin MKL, Kaas JH. Cortical connections of the visual pulvinar complex in prosimian galagos (*Otolemur garnetti*). *J Comp Neurol.* 2009; 517:493–511. [PubMed: 19795374]
- Wong-Riley M. Changes in the visual system of monocularly sutured or enucleated cats demonstrable with cytochrome-oxidase histochemistry. *Brain Res.* 1979; 171:11–28. [PubMed: 223730]
- Wu CW, Kaas JH. Somatosensory cortex of prosimian galagos: physiological recording, cytoarchitecture, and corticocortical connections of anterior parietal cortex and cortex of the lateral sulcus. *J Comp Neurol.* 2003; 457:263–292. [PubMed: 12541310]
- Wu CW, Bichot NP, Kaas JH. Convergent evidence from microstimulation, architecture, and connections for multiple motor areas in the frontal and cingulate cortex of prosimian primates. *J Comp Neurol.* 2000; 423:140–177. [PubMed: 10861543]
- Wu CW, Bichot NP, Kaas JH. Somatosensory areas S2 and PV project to the superior colliculus of prosimian primate, *Galago garnetti*. *Somatosens Mot Res.* 2005; 3:221–213. [PubMed: 16338830]
- Zilles K, Rehkämper G, Stephan H, Schleicher A. A quantitative approach to cytoarchitectonics. IV. The area pattern of cortex of *Galago demidovii* (ed. Geoffroy, 1796) (lorisidae, primates). *Anat Embryol (Berl).* 1979; 157:81–103. [PubMed: 517760]

Figure 1.

Cortical organization of prosimian galagos and tracer injection methods. **A:** The current understanding of cortical organization of prosimian galagos based on Fang et al. (2005) and Kaas and Lyon (2002). Areas include primary visual area (V1), secondary visual area (V2), the third visual area (V3), dorsomedial area (DM), dorsolateral area (DL), middle temporal area (MT), middle temporal crescent (MTc), medial superior temporal sulcus (MST), the fundus of the superior temporal sulcus (FST), inferior temporal cortex (IT), auditory cortex (A), primary somatosensory cortex (3b/S1), motor cortex (M), premotor dorsal area (PMD), premotor ventral area (PMV), orbital frontal cortex (Of), and the granular frontal cortex (Gr). LS is the lateral sulcus, IPS is the intraparietal sulcus, and FS indicates the frontal

sulci. **B:** A dorsal view of the galago brain showing the location of the lesion in the left hemisphere in order to access the superior colliculus for injections. **C:** A close-up view of the aspirated cortex with a view of the superior colliculus. The right hemisphere was retracted slightly in order to view and inject the right superior colliculus.

Figure 2.

Coronal sections of the superior colliculus stained for cytochrome oxidase (CO: **A**) or acetylcholinesterase (AChE: **B**). Photographs are taken from two different galagos. SZ, stratum zonale; SGS, stratum griseum superficiale; SO, stratum opticum; SGI, stratum griseum intermediale; SAI, stratum album intermediale; SGP, stratum griseum profundum; SAP, stratum album profundum. Medial is left. Scale bar = 1 mm.

Figure 3.

Cortical projections to the superficial and intermediate layers of the superior colliculus (SC) in case 07-111. **A:** The distribution of retrogradely labeled cells within flattened cortex after a fluoro-ruby (FR) injection into the SC. Gray dots represent FR cells. Solid lines represent borders determined using CO or myelin stains while dashed lines are estimated borders based on measurements and locations relative to other landmarks. The gray shaded area is cortex that was within sulci or along the medial or ventral surfaces. **B:** Dorsal view of the SC with the location of the FR injection site. **C:** Photomicrograph of the injection site within the SC. **D:** Photomicrograph of the adjacent section stained for CO. Scale bars = 5 mm in A; 0.5 mm in C,D.

08-40

A

B

Figure 4.

Cortical projections to the superficial and intermediate layers of the SC in case 08–40. **A:** Reconstruction of CTB-labeled cells in flattened cortex. **B:** Dorsal view of the injection site within the SC. **C:** Photomicrograph of a section stained for myelin indicating the location of MT, MST, MTc, and FST. **D:** Close-up view of the labeled cells within the MT complex region. Scale bars = 5 mm in A; 2 mm in C,D.

07-105

Figure 5.

Cortical projections to the superficial and intermediate layers of the SC in case 07-105. **A:** The distribution of retrogradely labeled cortical cells in flattened cortex after injections into the superficial and intermediate layers of the SC. Red dots represent retrogradely labeled cells from the FR injections while black dots represent retrogradely labeled cells from the CTB injection site. **B:** Our reconstruction of the injection sites on a dorsal view of the SC, with red representing the FR injection site and gray representing the CTB injection site. Visuotopic information is based on Lane et al. (1973). **C:** A photomicrograph of a coronal section of the SC with part of the CTB injection site. The injection site is mainly limited to the superficial layers of the SC. **D:** A photomicrograph of the coronal section of the superior colliculus with part of the FR injection site with the injection site located within superficial and intermediate layers of the SC. **E:** A photomicrograph of a myelin section showing the

location of MT, MTS, FST, and MTc. **F:** Close-up view of the location of retrogradely labeled cells with respect to E. Scale bars = 5 mm in A; 0.5 mm in C,D; 2 mm in E,F.

Figure 6. Cortical projections to superficial, intermediate, and deep layers of the SC in case 09-34. **A:** The distribution of CTB (black) and FR (red) retrogradely labeled cells within flattened cortex after injections into the superior colliculus that involved superficial, intermediate, and deep layers of the SC. **B:** Dorsal view of the SC indicating the locations of the CTB (gray), and FR (red) injection sites. **C:** A myelin stained section cut parallel to the brain surface showing the locations of MT, MST, FST, and MTc. **D:** Close-up view of the labeled cells within the MT complex region. **E:** Photomicrograph of the FR injection site within a coronal brain section through the SC. **F:** A photomicrograph of an adjacent section to E stained for

CO. **G:** Photomicrograph of the location of the CTB injection site within a coronal view of the SC. **H:** Photomicrograph of the adjacent CO-stained section to G. **I:** Photomicrograph of CTB-labeled cells within occipital cortex. Scale bars = 5 mm in A; 2 mm in C,D; 1 mm in E–H; 50 μ m in I.

Figure 7.

Cortical projections to superficial, intermediate, and deep layers of the SC in case 09-03. The distribution of retrogradely labeled CTB cells within flattened cortex after a CTB injection into the deep, intermediate, and superficial layers of the SC. **B:** Dorsal view of the injection site within the SC. **C:** Photomicrograph of a coronal AChE section at the location of the injection site core within the SGI. **D:** Photomicrograph of a coronal section stained for CTB showing the tracer spread through the full layers of the SC. Scale bars = 5 mm in A; 1 mm in C,D.

TABLE 1

Antibody Characterization

Antigen	Immunogen	Manufacturer	Dilution factor
Cholera toxin subunit B	Purified CTB isolated from <i>Vibrio cholerae</i>	List Biological Laboratories (Campbell, CA), goat polyclonal #703	1:5,000

TABLE 2
Percentage and Numbers of Cells Projecting to the Superior Colliculus From Various Cortical Regions and Areas

# cells in visual areas																						
Case#	Tracer	Inj Depth	Occipital Cortex					Temporal Cortex					Parietal Cortex					Frontal Cortex				Total
			V1	V2	V3	DM	DL	MT	MTc	MST	FST	IT	And	PPC	S2/PV	3b/S1	M	FEF	PMD	PMV	other	
07_105	FR	S and I	1049	196	13	11	20	0	0	3	34	39	3	3	0	0	4	NA	22	0	29	1426
	%#		73.6	13.7	0.91	0.8	1.4	0	0	0.2	2.4	2.7	0.2	0.21	0	0	0.3	NA	1.54	0	2.03	
	CTB	S	667	65	64	0	75	30	0	59	113	486	13	19	5	1	1	NA	3	0	59	1660
07_111	%#		40.2	3.92	3.86	0	4.52	2	0	3.6	6.8	29	0.8	1.14	0.3	0.06	0.1	NA	0.18	0	3.55	
	FR	S	1336	76	42	48	69	0	0	0	85	34	2	12	0	0	0	NA	7	2	35	1748
	%#		76.4	4.35	2.4	2.7	3.95	0	0	0	4.9	1.9	0.1	0.69	0	0	0	NA	0.4	0.114	2	
08_40	CTB	S and I	1343	99	73	0	174	21	0	61	157	204	3	5	0	0	0	NA	5	0	343	2488
	%#		54	3.98	2.93	0	6.99	1	0	2.5	6.3	8.2	0.1	0.2	0	0	0	NA	0.2	0	13.8	
			1810	1340	524	807	1044	13	N/A	34	510	1020	73	5361	187	15	37	NA	1411	1182	1970	17338
09_03	%#		10.4	7.73	3.02	4.7	6.02	0	0	0.2	2.9	5.9	0.4	30.9	1.08	0.09	0.2	NA	8.14	6.817	11.4	
	CTB	S, I, & D	6912	2586	2566	455	844	4	0	58	125	1473	0	2736	9	0	0	227	472	1003	235	19705
	%#		35.1	13.1	13	2.3	4.28	0	0	0.3	0.6	7.5	0	13.9	0.05	0	0	1.2	2.4	5.09	1.19	
09_34	FR	S, I & D	3297	862	203	22	170	2	0	11	166	130	0	117	0	1	0	9	30	67	8	5095
	%#		64.7	16.9	3.98	0.4	3.34	0	0	0.2	3.3	2.6	0	2.3	0	0.02	0	0.2	0.59	1.315	0.16	