THE KINESTHETIC CORTICAL AREA ANTERIOR TO PRIMARY SOMATIC SENSORY CORTEX IN THE RACCOON (*PROCYON LOTOR*)

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ABSTRACT

THE KINESTHETIC CORTICAL AREA ANTERIOR TO PRIMARY SOMATIC SENSORY CORTEX IN THE RACCOON (PROCTON LOTOR)

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Extracellular microelectrode recording was utilized to systematically explore the anterior border of the primary somatic sensory area in the raccoon. This was performed in order to delineate the extent and organization of the zone of muscle afferent (kinesthetic) projections, reported in other species to lie between the primary sensory and motor cortical areas. In 14 raccoons anesthetized with methoxyflurane, or with Dial-urethane, unit-cluster cortical activity was evoked in response to mechanical stimulation (including 100 Hz vibration) applied to the muscles of the dissected contralateral forearm and hindlimb, or to the separated integument. Once identified, the cortical cytoarchitecture of the kinesthetic area was examined.

Kinesthetic responses were recorded: in the anterior bank of the medial central sulcus excluding its most lateral end, and in the fundus and posterior bank of its medial arm; in the anterior bank of the medial end of the lateral central sulcus; and in the anterior two-thirds of the interfundic rise within the

interbrachial sulcus. Somatotopy of the muscle afferent projections was evident with forearm representation lateral to hindlimb, and proximal appendages representation caudal to distal appendage. The majority of the kinesthetic area represented flexors and extensors of the carpus and digits.

Within the kinesthetic area there was convergence of muscle representation for muscles which acted about a common joint. There was also convergence of cutaneous and muscle afferent projections in all kinesthetic unit-clusters recorded, with muscle units being of larger amplitude than cutaneous units in kinesthetic cortex.

The zone of muscle afferent projections was located anterior to S-I where the outer stripe of Baillarger and granular layer IV become attenuated. In the distal antebrachial muscle representation area all six cortical layers are evident. In the hindlimb muscle representation area, the criteria of Hassler and Muhs-Clement for cytoarchitectonic area 3a are met. The interfundic rise within the interbrachial sulcus has a polymorphous cytoarchitecture, representing distal antebrachial muscles laterally, and scapulo-thoracic muscles medially.

This thesis is dedicated to Doris P. Feldman, my wife. Without her its completion would not have been possible or nearly as meaningful.

To all the animals who suffer so that humans may better understand the principles of life.

By furthering our understanding of neuroscience, we hopefully will better understand ourselves.

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LIST OF ABBREVIATIONS

CNS	central nervous system
C	claw
D	dorsal
DAB	diaminobenzidne tetrahydrochloride
DCN	dorsal column nuclei
ECu	external cuneate nucleus
G - 1	guard hair type 1 mechanoreceptors
HRP	horseradish peroxidase
Hz	cycles per second (hertz)
HZ	zone of heterogeneous projections
IB	interbrachial sulcus
KVB	kinesthetic area of the ventrobasal complex
L	lateral
LC	lateral central sulcus
LCN	lateral cervical nucleus
M	medial
M-I	primary motor cortex
MC	medial central sulcus
MGNm	medial geniculate nucleus magnocellular aspect
mm	muscles; millimeter if preceeded by a number
MT	medial tongue of the ECu
Nx	nucleus x of the medulla
Nz	nucleus z of the medulla

PBS	phosphate buffered saline
PO	posterior nuclei of the thalamus
RA or ra	rapidly adapting evoked responses
S	response evoked by 100 Hz vibratory stimulus
S	no response evoked by 100 Hz stimulus
SA or sa	slowly adapting
SAαHz	frequency locking 100 Hz driven response
S—I	primary somatic sensory cortex
S—II	secondary somatic sensory cortex
ST	spinothalamic tract
STc	pars caudalis (spinal) trigeminal nucleus
STi	pars interpolaris (spinal) trigeminal division
STn	principal trigeminal nucleus
STo	pars oralis (spinal) trigeminal division
TBS	tris buffered saline
TMB	tetramethyl benzidine
TRI	triradiate sulcus
μl	microliter
μm	micrometer
VB	bentrobasal complex of the thalamus
VL	ventrolateral nucleus of the thalamus
VPI	ventroposterior inferior thalamic nucleus
VPL	ventroposterior lateral thalamic nucleus
VPM	ventroposterior medial thalamic nucleus

SECTION 1: INTRODUCTION

This thesis research involved a systematic exploration of the cerebral cortical area anterior to primary somatic sensory cortex (S-I) in the raccoon. The techniques of extracellular microelectrode mapping of evoked cortical potentials and light microscopic evaluation of Nissl cytoarchitectonics were the principal methods of investigation. This area of cortex had been previously mapped only in the region anterior to the S-I representation area of digit 4 (Johnson, et al., 1982).

This dissertation research was prompted by some questions about the raccoon kinesthetic cortical area, not addressed in the previous study of Johnson and his co-workers. In the remainder of the introduction these questions will be posed followed by some background information about kinesthetic cortex in primates, the domestic cat and the raccoon.

What are the boundaries (or extent) of the zone of the muscle afferent projections anterior to S-I in the raccoon?

In monkeys and the cat, rapidly adapting muscle afferent projections have been described in the anterior bank and fundus of the central sulcus and region of the

post-cruciate dimple, respectively (see Jones and Porter, 1980; discussed later in Section 2.5.c). This has not been addressed in the anterior somatic sensory area of the raccoon where the central sulcus is often interrupted by an intervening gyral bridge (Johnson, et al., 1982) into separate lateral and medial arms.

What is the cytoarchitecture of the kinesthetic zone in the raccoon?

In the rhesus macaque and the cat, kinesthetic cortex was characterized as having unique cytoarchitecture. This sensorimotor cortical area was identified as that designated Area 3a by Brodmann (1906) in primates and later described in the cat (Hassler and Muhs-Clement, 1964) on the basis of cortical cytoarchitecture. In the article by Johnson (et al., 1982) it was noted that the muscle afferent zone in the raccoon did not possess the cytoarchitectonic criteria of Area 3a, described in the cat and monkey.

Is there somatotopic organization of muscle afferent projections to anterior S-I in the raccoon?

In both the cat and monkey, Area 3a contains a crude somatotopically organized representation of the "deep" musculoskeletal tissues (Jones and Porter, 1980). In general the body representation in Area 3a is oriented with the hindlimb area lying medial to the forearm area similar to the cutaneous representation in S-I proper (Area 3b).

Is 100Hz low amplitude vibratory stimulus applied directly to the dissected muscle belly an effective means of evoking kinesthetic cortical activity?

This question is prompted by two facts. First is the ambiguity of receptors being stimulated in "deep" tissues by applying pressure through the skin. Second is the nature of cortical activity in the phenomenon known as the vibration-induced illusion (Goodwin, et al., 1972a, 1972b, 1972c). When 100Hz vibration is applied transversely to the tendon of a muscle in the conscious human, it produces an illusion of stretching of the muscle belly.

This thesis research addresses the nature of the relationship between the zone of muscle afferent projections to anterior S-I and the cytoarchitecture of this cortical area of the raccoon. It utilizes 100Hz vibratory stimuli to map the extent and somatotopic organization of the raccoon kinesthetic zone anterior to S-I. From this study inferences will be made about cortical organization in the kinesthetic area and the parameters which influence the gross sulcal folding of the central sulcus in the raccoon.

Why has the raccoon been chosen the subject for this research?

The raccoon was chosen as the experimental subject for several reasons. This species is plentiful in the wild and easily obtained. Raccoons are relatively simple to maintain in captivity as compared to primates. As an

erimental subject raccoons seem to draw less of a ane concern from the general public as compared to earch on domestic animals, such as the dog and cat. The coon has unique "gigantism" of glabrous forepaw repre- ation in S-I cortex, reminiscent of hand representation n in primates, and more dramatic than the forepaw esentation in canine and feline S-I (Walker and lenstein, 1959).

According to recent experimental findings medullo- lamic kinesthetic projections in the raccoon are more ilar to the primate than are those of the cat. In mates the external cuneate nucleus (ECu) projects to an erodorsal nuclear shell about the ventroposterior nuclei the thalamus (Bovie and Bowman, 1981). So far this is only known pathway whereby kinesthetic information is veyed to the thalamus enroute to Area 3a in monkeys. feline ECu projects exclusively to the cerebellum not to the thalamus (Rosen, 1969; Berkley, 1980). a recent study of kinesthetic projections from the ulla to the thalamus in the raccoon, Ostapoff (1982) cribed a group of cells comprising 20% of the external eate which projected to a kinesthetic nuclear shell ut the ventrobasal complex (Wiener, 1983). Therefore, raccoon may be a better model for primate kinesthesia n the cat, based on central pathways conveying esthetic information to cortex.

The raccoon is an excellent subject for examining the relationship of cortical cytoarchitecture to incoming thalamic afferent sensory submodality. As previously discussed, Area 3a was defined as a distinct cytoarchitectonic field prior to its being described as a submodality specific sensory cortical area in cats and monkeys (see Jones and Porter, 1980). Johnson (et al., 1982) reported that no cytoarchitectonic Area 3a was found in raccoons by Brodmann's (1906) criteria but a zone of kinesthetic cortex was located in the anterior bank of the central sulcus, similar to primates and like the post-cruciate dimple area of the cat. Therefore, Johnson and his co-workers speculated that muscle projections to anterior S-I are associated more with central sulcal folding, in all species thus far examined, and less so with a specific cortical cytoarchitecture. This is true of kinesthetic cortex in the central sulcus of monkeys where cyto-architectonic Area 3a is located most consistently in the hand representation area of S-I (Jones and Porter, 1980). This thesis examines the entire extent of kinesthetic cortex for uniformity and distinctiveness of its cytoarchitecture compared with that of S-I and primary motor cortex in the raccoon.

SECTION 2: LITERATURE REVIEW

Section 2.1.0: Mechanosensation

In order to understand the basis for the conscious kinesthetic sense in humans a review of the mechanoreceptors and central neural pathways which give rise to these sensations are presented in the following literature review. The conveyance of kinesthetic and cutaneous tactile information follow similar, but submodality specific, pathways to unique areas within primary somatic sensory cortex. Kinesthetic and cutaneous representation areas are cytoarchitecturally distinct in S-I of rhesus monkeys and cats, but less so in other species of monkeys (Jones and Porter, 1980) and raccoons (Johnson, et al., 1982).

Historically, electrophysiologic mapping has been the primary technique utilized to investigate the central nervous system (CNS) areas receiving somatic sensory afferents (for examples see Adrian, 1943; Woolsey and Fairman, 1946; Mountcastle and Henneman, 1949; Welker and Seidenstein, 1959). Specific cerebral cortical areas were identified in which neural activity was evoked by mechanical stimulation of peripheral cutaneous mechanoreceptors. As electrophysiologic mapping progressed

several principles of mammalian central somatic sensory organization became apparent (i.e. laterality, somatotopy, nonconvergence, receptive field size, etc.) (see Walker, 1973; Johnson, 1980). Cutaneous areas of high sensory receptor density are those utilized most by a species in tactile discrimination of its environment (Brown and Iggo, 1967). Areas of high cutaneous receptor density have receptive fields defined electrophysiologically in proportionately larger volumes of central sensory nuclei (Welker, 1973). As stated by J.I. Johnson, Jr. (1980, p. 436), "Regions of great receptor density will project in regions of greater cell number and nuclear volume in the brain, and in extreme cases these central regions show a well defined organization into separate lobules or subnuclei corresponding to receptor dense regions which are spatially separated from one another on the body surface." In primary somatic sensory cortex cutaneous receptor density is reflected in the gyral and sulcal topography (Johnson, 1980).

Many submodalities of mechanoreception can be distinguished by varying the method of stimulation of the peripheral body utilized to evoke neural activity in the CNS. As the techniques of microelectrode mapping of evoked neural activity became more refined, it has become apparent that at least some mechanosensory submodalities are segregated into separate central nuclear representation, in the medulla (cat: Dykes, et al., 1982; raccoon:

Ostapoff, 1982), in the thalamus (monkey: Whitsel, et al., 1978; Dykes, et al., 1981; Jones, et al., 1982a,b; raccoon: Wiener, 1983) and in S-I (monkey: Merzenich, et al., 1978; Kaas, et al., 1979; Nelson, et al., 1980; Sur, et al., 1982; cat: Dykes, et al., 1980; Dykes and Gabor, 1981; raccoon: Johnson, et al., 1982).

Proprioception in mammals can be divided into vestibular (accelerational both static-gravitimetric and dynamic) and kinesthetic (positional both static and dynamic) components. Vestibular proprioceptive receptors are located in the semicircular canals, utricle and saccule of the inner ear. The receptors transducing kinesthetic information are located in muscles, tendons, ligaments and joints with some small cutaneous contribution (McCloskey, 1978).

The integument contains mechanoreceptors associated with the sense of touch. The integument forms a contiguous body covering, being essentially a two-dimensional surface enveloping three-dimensional space. Receptors for kinesthetic information are distributed in a more discontinuous fashion being parcelled between muscle bellies, joint capsules, and their associated tendons, ligaments and periosteum. The significance of peripheral receptor distribution and density was mentioned before, and will be repeated at this point.

The density of cutaneous receptors is higher in body areas utilized most by a species in the tactile exploration

of its environment (Brown and Iggo, 1967). Whether this is also true for kinesthetic projections from receptors sensitive to tactile body part position has been less well studied but appears to be true (discussed in section 6.2, page 174). Cutaneous areas of high receptor density project to proportionately larger central sensory nuclear volumes of greater cell density (Welker, 1973; Johnson, 1980) ultimately being represented over a greater surface area of S-I cortex, as compared to receptor sparse cutaneous areas. Kinesthetic central receptive field representation is more functionally oriented with convergence of information from mechanoreceptors in muscles that act similarly at a joint.

There is a cutaneous component to kinesthetic information as muscular action that leads to alteration in the angulation and forces exerted at a joint, also cause local deformation of skin about the joint and at the integument where the muscular forces are exerted (McCloskey, 1978). Therefore it should not be a surprise that there is some convergence of (electrophysiologically recorded units which respond to both) kinesthetic and cutaneous mechanoreceptors where their peripheral receptive fields overlap.

In the succeeding literature review only sensory afferent projections and central sensory nuclei relaying toward S-I and S-II directly are discussed. Thermoreceptive and nociceptive projections are ignored beyond

their contribution to the medial lemniscus. The reader will become acquainted with cutaneous and kinesthetic mechanoreceptors, their central projections and central nuclear representation and body surface representation in S-I and S-II.

Section 2.1.0.a: Receptors for Cutaneous and Kinesthetic Mechanosensation

The following section catalogs some known sensory mechanoreceptors found in the integument, muscles, tendons, ligaments and joints. For each receptor type a summary is given of evoked electrophysiological characteristics. The classification system of afferent sensory axons is presented. This section is derived largely from reviews of mechanoreceptors and their primary afferent characteristics by Brown (1981), McCloskey (1978) and Angel (1977).

Section 2.1.1: Cutaneous Mechanosensory Receptors

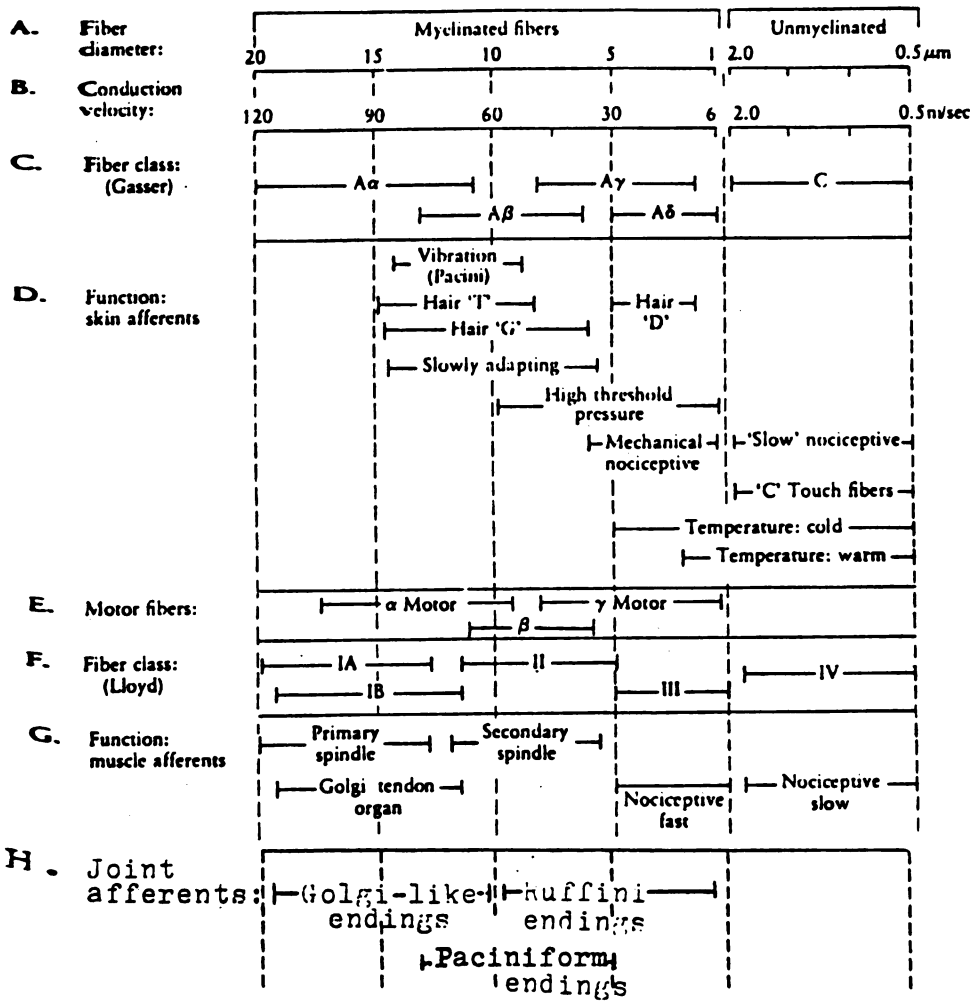
Three major groups of receptors can be distinguished on the basis of their temporal response to evoked stimulus application (Angel, 1977). First are those which respond with a tonic action potential discharge frequency directly related to stimulus intensity, slowly-adapting position detectors. Secondly are mechanoreceptors responding with a phasic discharge related to the rate of change of stimulus intensity, rapidly adapting velocity detectors.

Lastly are those which discharge at onset and termination of stimulation, rapidly-adapting transient detectors.

There are two types of skin containing receptors, hairy skin and thick glabrous skin lacking hairs. Glabrous skin is located in such areas as the weight bearing surfaces of the manus and pes, the labia and nares, and elsewhere. In the cat five categories of hairs have been described in the hairy skin (Noback, 1951; Brown and Iggo, 1967): (1) Down, the most numerous hairs in the undercoat of thinnest diameter. (2) Awn, as thin as down hairs at the base becoming thicker at the apex. (3) Guard, thicker at the base than awn or down also increasing in diameter toward the apex. (4) Tylotrich a type of guard hair in close proximity to specialized epidermal sensory structures called Type 1 domes (discussed below) and having modified follicles. (5) Sinus hairs, specialized tactile hairs like vibrissae, carpal hairs or muzzle hairs.

Primary sensory afferent nerve fibers have been classified according to diameter (which is directly proportional to conduction velocity). Two systems have been used; a system for sensory nerves from muscles, joints or tendons (Lloyd, 1943) classified as groups I through IV: a system for cutaneous sensory nerves Aα, Aβ, Aγ, Aδ, and C groups (Gasser, 1960). Table 2-1 shows the sensory nerve fiber classifications, diameters, conduction velocities and associated mechanoreceptors. All primary afferent axons are myelinated except group

Table 2-1: Characteristics of peripheral axons and their associated receptors in mammalian species (Adapted from Shepherd, 1983).



IV and C-fibers which have identical properties. Cutaneous receptors whose response is conducted along A-fibers tend to be transient detectors with little directional sensitivity (Angel, 1977). Receptors assocated with well anchored cutaneous structures (e.g. claws or sinus hairs) relay information about static position. C-fibers transmit information from receptors sensitive to the linear directionality of stimulus.

Section 2.1.1.a: Cutaneous Transient Detectors

G-1 hair receptors: These respond to movement of the longest guard hairs at high velocity (20 mm/s) in large sinusoidal displacements (above 60 Hz) or small sinusoidal displacements (above 200 Hz). These are the least sensitive of the hair follicle receptors that have been reported in the cat (Brown and Iggo, 1967) and monkey (Perl, 1968; Merzenich and Harrington, 1969). Their afferent fibers conduct in the A range.

Pacinian corpuscles: Located in deeper tissues these are stimulated by skin indentations as small as 1μm from 150-400 Hz (Merzenich and Harrington, 1969). Clusters of Pacinian corpuscles are found in the vicinity of feline carpal hairs that respond to rapid hair movement (Nilsson, 1969). These conduct in the Aα range.

Vibrissal transient receptors: Activated by movement of a single vibrissae, these receptors have been reported

in the rat (Zuker and Welker, 1969) and cat (Gottschaldt, et al., 1972).

Section 2.1.1.b: Cutaneous Velocity Detectors

Hair receptors: G-2 (guard) hairs respond to slow hair movement (0.5-1.5 mm/s) and also display properties similar to the G-1 transient detectors (Burgess et al., 1968) having a short lived discharge after movement. Tylotrich hairs are velocity receptive and have Type-1 touch corpuscles (discussed below) associated with them (Brown and Iggo, 1967; Burgess, et al., 1968). Down hair receptors respond to very slow hair movement, imparting some position sensitivity. All the above hair receptors conduct in the A-fiber velocity range. Some sinus hair receptors in the rat show properties of velocity detection but are sensitive only to certain linearly directed displacements (Zucker and Welker, 1969).

Receptors in hairy skin: These are not stimulated by movement of the hair alone but require visible displacement of adjacent skin (Burgess, et al., 1968). These are designated field receptors, being rapidly adapting, and conducted along Aα-fibers. Threshold displacements were about 80μm.

Receptors in glabrous skin: Having properties similar to field receptors, these have been found in foot and toe pads of cats (Janig, 1971), primates (Lindblom, 1965),

man (Hagbarth, et al., 1970), and in raccoons (Barker and Welker, 1969; Pubols, et al., 1971).

Section 2.1.1.c: Cutaneous Position/Velocity Detectors

Sinus hairs: Associated with static displacement sensitivity, these mechanoreceptors possess some velocity sensitivity when moved from rest and exhibit spatial directionality (firing to displacement in one quadrant of a circle from rest position) (Iggo, 1968; Zuker and Welker, 1969).

Hairy skin: The position/velocity receptors designated Types I and II are distinguished both morphologically and functionally (Iggo, 1966). Type I receptors are slowly adapting, discharge in an irregular manner and consist of a single afferent nerve fiber supplying 1 to 5 dome-like elevations of the skin. The nerve fiber in each dome supplies a number of Merkel cells located below the epithelial stratum basale (Iggo and Muir, 1969). Type I receptors respond to gentle touch. Type II afferent fibers are associated with a single skin spot overlying a Ruffini nerve ending (Chambers et al., 1972). Both receptor types have been reported in primates (Perl, 1968) and Type I receptors have been found in the cat (Smith, 1970). In rabbits a type I receptor is associated with all tylotrichs located on the lips (Brown and Iggo, 1967).

Glabrous skin: There are receptors morphologically and functionally similar to Type I receptors in hairy skin (i.e. Merkel cell associated; Janig, 1971) found in the glabrous skin of the cat. Type II receptors have been found in primate glabrous skin (Perl, 1968).

C-fiber afferents: These supply receptors in both hairy and glabrous skin that are sensitive to the linear directionality of stimulus and, have an after discharge at stimulus withdrawal (Besson, et al., 1971). The frequency of C-fiber action potentials is linearly related to amount of skin identation.

Section 2.1.2: Kinesthetic Mechanoreceptors

Mechanoreceptors in a variety of noncontiguous locations contribute to the kinesthetic sense (McCloskey, 1978). Much of the data accumulated as to the role of various peripheral mechanoreceptors in the kinesthetic sense comes from experiments on human subjects. In these experiments receptors were differentially anesthetized and the subjects asked to comment on imposed changes in appendage position which they could not visualize. From these studies it was concluded that large deficits in proprioceptive acuity occur when joints and skin are anesthetized while innervation of relevant muscles is preserved intact (Gandevia and McCloskey, 1976). A different group of investigators felt that digital kinesthetic acuity is diminished by joint-cutaneous

anesthesia, but remains fairly acute if reasonable muscle tone exists on the tendons to the appendage at which passive movement is being imposed (Head and Sherren, 1905; Stopford, 1926; Brown, et al., 1954; Goodwin, et al., 1972a,b,c). To elucidate the large contribution of muscle spindle input to the conscious proprioceptive sense, three phenomena have particular relevance. These are the "phantom limb", vibration induced illusions and the proprioceptive sense (more accurately its lacking) in the extraoccular muscles.

The "phantom limb" is an illusion experienced by amputees that the amputated part still exists, and can change its perceived position in space in response to conscious motor effort. More distal points on an appendage are more strongly perceived, roughly proportional to the central representation of the part in somatosensory cortex (Penfield and Boldrey, 1937). If the stump bearing the phantom limb is moved in relation to the rest of the body, the phantom limb always is experienced to move, too. If the amputee is asked to move the phantom limb a specific way, twitching of appropriate muscles in the stump can be seen grossly as the subject says the movement is accomplished (Riddoch, 1941; Henderson and Smythe, 1948). By cutting muscle innervation to the stump the ability to move the "phantom limb" was felt to be lost by the amputees. This seems to indicate that muscle afferent activity is perceived as a conscious kinesthetic

sense in the absence of joint and tendon afferents in man.

When the tendon of a muscle is vibrated longitudinally along its course at 100 Hz, a human subject will perceive that the joints at which the muscle acts are moving in a direction that would stretch the vibrated muscle (Goodwin, et al., 1972a,b), even when sensory afferents from the affected joints have been anesthetized (Goodwin, et al., 1972c). This type of stimulus has been shown to strongly activate muscle spindle receptors without activating joint or tendon organ receptors. No illusory movement occurs when similar vibration is applied over a joint. Even when all the joints and skin of the hand are anesthetized, vibration of the digital flexor tendons causes illusory sensation of extension of the hand and fingers (Goodwin, et al., 1972c). The contribution of receptors in tendons should not be ignored, but muscles and their respective tendons always act in unison even in isometric contraction.

Eye muscles are among the fastest contracting in the body (Kandel and Schwartz, 1981, p. 395). Unlike other striated muscles, the extraocular muscles do not pull against gravity and have a very sparse population of muscle spindles. The eye muscles lack the spindle reflex (Kandel and Schwartz, 1981, p. 401). The extreme rapidity of eye movement stems from the higher firing rate of ocular motor neurons (400-600/sec), as compared to spinal motor neurons (50-100/sec), and their lack

recurrent inhibition. The extremely rapid conjugate eye movement called a saccade is responsible for rapidly directing our retinal foveas toward a target of interest in our visual field, and comprises the rapid phase of vestibulo-ocular and optokinentic nystagmus. To initiate the saccade requires no cognizance of the ocular position in the orbit, they can be initiated with the eyes closed.

Brindley and Merton (1960) were interested with the question of the ocular propioceptive sense in the face of a sparse spindle population. They anesthetized the surface of one eye in their subjects and held it motionless with forceps to prevent its movement. Both eyes were then visually occluded. The subject was asked to initiate a saccade or slow eye movement which only the free roaming eye was able to accomplish. In these experiments the subjects were unable to tell the investigators whether the stationary eye had also achieved the intended movement. These authors concluded that if voluntary eye movements are artificially impeded or passive movements imposed, we consciously do not know the position of the ocular axis. The ocular proprioceptive sense relies more heavily on visual feedback than muscle spindle input.

The studies on "phantom limbs", vibratory illusion and ocular proprioception lend support to the idea of muscle spindles playing a major role in the kinesthetic sense. There are several mechanoreceptor types which transduce kinesthetic information of which muscle spindles

are only one. The following section catalogs some of these kinesthetic receptor types. Cutaneous contributions to kinesthesia are not discussed.

Section 2.1.2.a: Joint Receptors

Three specialized mechanoreceptor endings exist in most joints: Ruffini endings, Golgi-like endings and encapsulated paciniform endings. These latter two types are located not in the joint capsule, but rather at the capsular and ligamentous attachments to periosteum adjacent to the joint. These joint receptors have been most extensively studied in the stifle of the cat.

Golgi-like endings: These are slowly adapting receptors in ligaments associated with a joint. The afferents from these receptors conduct in the Group I range. These receptors exhibit position sensitivity, being uninfluenced by tension of muscles inserting on the joint capsule. Maximal response from these receptors occur at or near full flexion or extension of the joint. For a review of this receptor type see Skoglund (1956).

Ruffini endings: Located in the fibrous joint capsule, these receptors are also slowly adapting in character. The afferent axons from these belong to Groups II and III. These are the most numerous of the joint receptors, and respond to angular displacement, static position and alterations in joint capsule tension brought about by muscles with points of insertion on

the fibrous joint capsule. This receptor type is sensitive to pressure on the joint capsule.

Paciniform-like endings: These are associated with joint capsule insertions on adjacent periosteum. The afferent axons from these receptors fall in the Group II category. These are rapidly adapting receptors responding to rapid changes in joint angle only during active movement (Burgess and Clark, 1969).

Section 2.1.2.b: Tendon Receptors

Golgi tendon organs (Houk and Henneman, 1967): These receptors are located within muscle tendons just beyond their attachments to muscle fibers. An average of 10 to 15 muscle fibers are connected in series with each tendon organ (in the cat). The tendon organ is stimulated by tension on the tendon (stretching) from muscle contraction. The tendon organ responds to onset of stretch with a burst of action potentials whose frequency is proportional to the rate of increasing tension. At a steady state of tension the tendon organ assumes a constant rate of firing proportional to the degree of tension. A lowering in the frequency of action potentials at tension offset is proportional to the rate of stimulus withdrawal. Thus, both tonic and phasic information is conveyed via Group I axons to the CNS.

Section 2.1.2.c: Muscle Spindles and Spindle Receptors (McCloskey, 1978)

The number of afferent fibers from the muscles that act at a common joint is ten-fold greater than the number of afferent fibers from the joint itself, as estimated in the cat (Goodwin, et al., 1972c). The importance of this lies in our premise that relative receptor density in the peripheral body is related to the proportion of central somatic sensory nuclear volume receiving afferent projections from a body part (Johnson, 1980).

Muscle spindles (Guyton, 1976) are composed of intrafusal muscle fibers with mechanoreceptors located in their noncontractile mid-equatorial region. They lie in parallel with extrafusal muscle fibers. There are two types of intrafusal muscle fibers distinguished by fiber diameter and nuclear arrangement. These are the large nuclear bag fibers and smaller nuclear chain fibers. The predominant spindle receptor associated with nuclear bag fibers is the primary (annulospiral) ending. Primary endings wrap around the intrafusal fiber equator, convey information on both the static and dynamic stretch of muscle, and conduct along Group I afferent axons. Nuclear chain intrafusal fibers usually possess both primary and secondary spindle receptor endings. Secondary spindle receptors (flowerspray) are located on either side of the primary ending, are sensitive to static stretch and conduct along Group II afferent axons. Primary endings

respond in a 1:1 manner with vibration applied to the tendon at frequencies of 100-500 Hz and less than 10μm displacement. Secondary endings and tendon organ receptors are largely insensitive to similar vibration applied to a tendon at low amplitude and high frequency (M.C. Brown, et al., 1967).

Section 2.2: The Afferent Pathways and Central Nuclei of Cutaneous and Kinesthetic Mechanosensations in the Cat, Monkey and Raccoon

The medial lemniscus is composed of a bundle of axons which contains three anatomically separate sensory pathways conveying information from the periphery to the contralateral thalamus (reviewed by: Angel, 1977; Welker, 1973). The pathways discussed individually in the succeeding subsections are the dorsal column-lemniscothalamic, the spinocervico-lemniscothalamic and the spinothalamic tracts.

Section 2.2.1: Spinocervico-Lemniscothalamic Pathway

This pathway is more highly developed in carnivores (Kitai and Winberg, 1968) than in primates (Ha and Morin, 1964; Truex, et al, 1970). The second order neurons of this pathway are located in Rexed's laminae III, IV and V; their axons ascending in the dorsolateral funiculus to ramify within the lateral cervical nucleus (LCN). Cells in LCN are excited almost exclusively by ipsilateral hair movement and rarely by input from receptors in glabrous skin of the rat, (Giesler et al., 1979).

Within the lumbosacral enlargement of the cats' spinal cord dorsal horn, a somatotopic map of the hindlimb has been delineated electrophysiologically (Wall, 1960; Bryan, et al., 1973; Brown and Fuchs, 1975). Second order sensory neurons in the lumbosacral laminae III, IV and V receive hindlimb primary afferent axons which are distributed as follows: distal and ventral hairy skin are represented medially, proximal and dorsal receptive fields are represented laterally. Evoked single unit activity recorded from adjacent spinocervical projecting neurons in the lumbosacral dorsal horn showed greater receptive field overlap in the sagittal plane (90%) than in the transverse plane (30%) (Brown, 1981). The receptive fields are represented by narrow columns of spinal dorsal horn cells, oriented rostro-caudally which are 1-2 cells wide.

Evoked cutaneous mechanosensory activity in the lateral cervical nucleus (LCN) is somatotopically organized (with little receptive field convergence) in the cat (Craig and Tapper, 1978) but not in the rat (Giesler, et al., 1979). In the cat hindlimb is represented dorsolaterally, forelimb is located ventromedially and face medial most within LCN. The LCN in the rat receives about 30% of its afferent input from nociceptive stimuli originating in large receptive fields which are convergent (or identical) with thermoreceptive input (Craig and Tapper, 1978). The cat LCN also receives a large input of

nociceptive projections (Brown and Franz, 1970). The majority of LCN neurons project to contralateral thalmic ventrobasal complex in the cat (Horrobin, 1966) and rat (Giesler, et al., 1979) via the medial lemniscus. The rat LCN receives up to 40% of its ascending mechanosensory input from contralateral body receptive fields. In carnivores the spinocervicothalamic pathway is reported to be the fastest pathway to cortex for somatic sensory information (Kitai and Weinberg, et al., 1968).

Section 2.2.2: The Spinothalamic Tract

There are three components which comprise the spinothalamic pathway. All three components originate from second order sensory neurons located mainly in spinal grey laminae IV and V (80%) but also in I, VI, VII and VIII in the monkey (Trevino, et al., 1973); and laminae VII and VIII (87%) (Trevino, et al., 1972) in the cat with some from V and VI.

The three component projections of these second order sensory neurons are (Angel, 1977):

1) Spinobulbar: tertiary neurons lie in the bulbar reticular formation gigantocellular division, projecting to VB and other thalamic relay nuclei,
2) Paleospinothalamic: tertiary neurons lie along the entire length of the brainstem reticular formation,
3) Neospinothalamic: this pathway has been reported in primates (Mehler, 1969) but not in cats (Boivie, 1971). The spinal secondary sensory neurons project directly to VB.

Section 2.2.3: Dorsal Columns and the Dorsal Column Nuclei

The dorsal columns traditionally were considered to be composed of primary somatic sensory afferent axons, which ramified in the cuneate-gracile nuclear complex (the dorsal column nuclei, DCN). Recently other sources of mechanosensory afferent input to the DCN have been recognized. In the cat about 25% of spinocervical axons projecting to the LCN send collaterals to the rostral portions of the DCN (Craig and Tapper, 1978). Non-primary axons ascending the dorsal columns do not all ramify within the dorsal column nuclei, as these project to nucleus intercalatus, nucleus Z, vestibular nuclei, the external cuneate nucleus, the solitary nucleus, area postrema and the tegmental grey matter (see Brown, 1981).

In general, afferent sensory projections to the DCN from hindlimb ascend the fasciculus gracilis and ramify in the gracile nucleus. The same can be said for the forelimb projections along the fasciculus cuneatus to the cuneate nucleus. Figure 2-1 depicts the dorsal column-lemniscal, spinothalamic and spino-cervical-thalamic pathways for cutaneous mechanosensation. The following subsection delineates the anatomical and electrophysiological characteristics of the dorsal column nuclei in the cat, monkey and raccoon. Several general principles of mammalian central sensory nuclei discussed are:

Figure 2-1:

A diagrammatic representation of the dorsal column - medial lemniscal - thalamic, spinocervical - lemniscal - thalamic and spinothalamic pathways for cutaneous mechanoreception from dorsal roots to cortex. These three afferent somatic sensory pathways comprise the majority of the medial lemniscus. The medial lemniscus projects from its spinal and medullary origins to terminate in a dense core fashion, centered within the thalamic ventrobasal complex (VB, surrounded by a concentric shell of less dense terminations in thalamic nuclei adjacent to VB (Berkley, 1980).

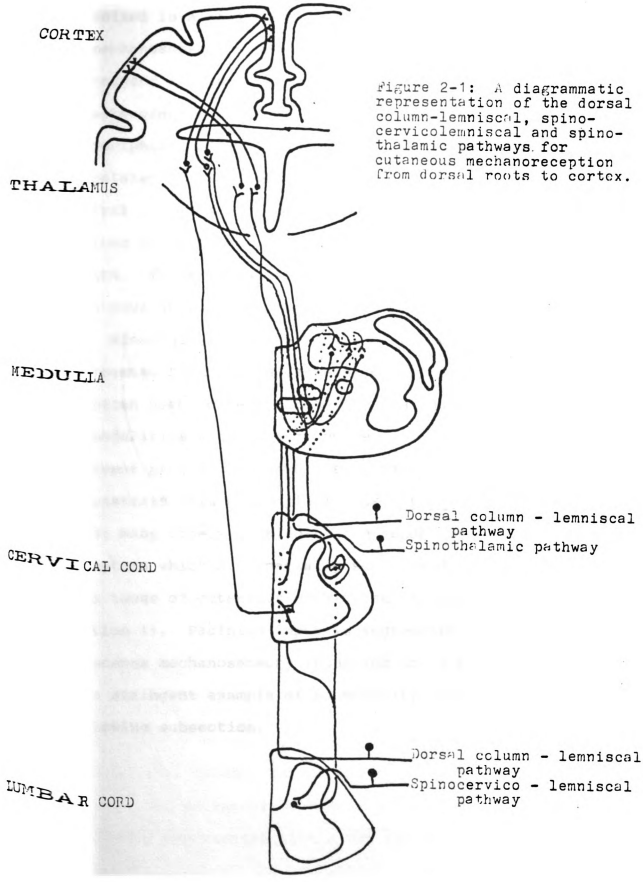


Figure 2-1: A diagrammatic representation of the dorsal column-lemniscal, spino-cervicolemniscal and spino-thalamic pathways for cutaneous mechanoreception from dorsal roots to cortex.

1) Afferent projections onto central nuclei are organized in a similar manner in all three species; 2) mechanosensory submodalities are preserved by non-convergent inputs to spatially segregated regions of the cuneate-gracile complex; 3) central nuclear volume devoted to peripheral body representation varies in a way which is related to peripheral receptor density; 4) there are central clusters of neuronal perikarya forming subnuclear regions which represent the distal forelimb glabrous digits. These subnuclei represent disjunctive areas of high cutaneous mechanoreceptor density.

Kinesthetic central nuclear representation is segregated from cutaneous mechanosensory representation and is often used to demonstrate the segregation of sensory submodalities with central nuclei. Traditionally, muscle afferent projections have been a favorite submodality to demonstrate this principle (Dykes, et al., 1972; Walker, 1973; many others). Kinesthetic sensation originates from receptors which are spatially segregated in the periphery from those of cutaneous origin (see introduction to Section 1). Pacinian input is segregated from other cutaneous mechanosensory input and so is presented as a more stringent example of submodality segregation in the following subsection.

Section 2.2.3.a: Dorsal Column Nuclei in the Cat

In a study of discrete rhizotomies of the dorsal roots at every segment of the spinal cord, Rustioni and Macchi (1968) used a degenerating axonal stain to study primary sensory afferent projections onto the dorsal column nuclei (DCN) in the cat. They concluded that fibers within the dorsal columns terminate in a pattern which shifts gradually from the nucleus gracilis to the nucleus cuneatus, as the origin of the projections progresses from caudal to rostral along the spine. Coccygeal, sacral and lumbar afferents caudal to L_5 project predominately to the gracile nucleus, while sensory afferents of dorsal roots cranial to and including L_5 terminate progressively more in the cuneate nucleus. Cervical roots project to the cuneate region and not the gracile nucleus. The projections did not show an abrupt demarcation at L_5.

These findings parallel those found in microelectrode mapping studies of DCN in the cat (Kruger, et al., 1961), that there is a functionally somatotopic representation of contiguous cutaneous receptive fields. Further, multiple body representations in generally somatotopic organization lay in separate central nuclear areas, each predominately submodality specific, organized as rostrocaudal columns in the DCN (Kuhn, 1949; Dykes, et al., 1982). The cutaneous mechanosensory somatotopy is generally represented with a cat lying with its dorsum

ventrally, its foot region medial in the gracile nucleus, body in cuneate and head lateral in the spinal trigeminal nucleus. Distal forelimb was represented by proportionately larger central nuclear volume dorsally compared to body and hindlimb (see Figure 2-2).

Dykes (et al., 1982) described the somatotopy of submodality specific regions in the DCN complex, not found in the spinal trigeminal nucleus, distinguishing deep and cutaneous rapidly adapting (RA), deep and cutaneous slowly adapting (SA) and pacinian input. The deep SA responses of the forelimb were found in the basal nuclear region of the cuneate and the external cuneate nuclei. The lateral gracile at its junction to the cuneate represented the deep SA responses of the hindlimb. Deep modalities tended to receive greater representation in the rostral third of the DCN, as compared to the caudal two-thirds. Both cutaneous SA and RA submodalities were found in a single somatotopic representation predominately in the rostral two-thirds of the main cuneate-gracile nuclear complex. Pacinian afferents showed a somatotopic organization similar to the SA and RA cutaneous afferents, preferentially distributed in the caudal third of the DCN. The digits of the forelimb, occupied most of the dorso-ventral dimension of the RA and SA cutaneous representation area found mainly in the middle third of the DCN rostrocaudal extent. Within the cuneate nucleus condensations of neuronal perikarya separated by laminae

Figure 2-2:

Depicted are transverse sections of caudal medulla oblongata in three species. The somatotopic distribution of primary afferents for cutaneous mechanosensation and central nuclear representation in the spinal trigeminal-cuneate-gracile nuclear complex are similar in all three species. Minor species differences exist in medullary origins of kinesthetic projections (see text). Drawings are extrapolated from histologic and electrophysiologic studies by: monkey - Carpenter, et al., 1968 (dorsal root ganglion rhizotomy degeneration study); cat - Keller and Hand, 1970 microelectrode mapping study); raccoon - Johnson, et al., 1968 (microelectrode mapping study). Abbreviations: external cuneate nucleus (E-Cu), spinal trigeminal nucleus (S.Tr.), cuneate-gracile complex (Cu-Gr), nucleus of the tractus solitarius (N.T.S.), vagal nucleus (N.X.), area postrema (Ar.P.), hypoglossal nucleus (H.N.), internal arcuate fibers (Int Ar F).

of incoming afferent fibers occur in the region of the glabrous paw representation in the cat.

Discontinuities in the somatotopy exist in the above study for deep and pacinian afferent terminations from the head. Deep mechanoreceptor projections from the head are found in the mesencephalic trigeminal nucleus, not in the spinal trigeminal nucleus. Projections of pacinian receptors in the head integument have not been found in either the spinal or mesencephalic portions of the trigeminal nucleus. In addition nuclear groups X and Z in the medulla receive muscle afferent projections (Rustioni and Molenaar, 1975). Nucleus X (Nx) is bordered laterally by the restiform body, rostrally by the descending vestibular nucleus and caudally by the external cuneate nucleus (ECu). Its major input is via Group I muscle afferents from the dorsolateral columns but not the dorsal columns. Both Nx and ECu project to ipsilateral cerebellar cortex. Nx also projects to more rostral contralateral brainstem. The ECu receives its afferent axons from the dorsal columns (Johanson and Silfvenius, 1977).

Nucleus Z (Nz) has proven to carry hindlimb Group I muscle afferent information along the sensory pathway to sensorimotor cortex (Landgren and Silfvenius, 1976). This nucleus is located just rostral to the anterior pole of the gracile nucleus, and receives its input from the dorsolateral columns (Rustioni and Molenaar, 1975).

The basal cuneate region located ventrally and caudally in the DCN likely carries Group I forelimb afferent information to sensorimotor cortex (Rosen, 1969a). Thus the DCN projects cutaneous mechanosensory information while the basal cuneate region and Nz project muscle spindle information, to sensory nuclei in the thalamic ventrobasal complex and adjacent thalamic nuclei (discussed in section 2.2.4.a).

The sensory trigeminal nuclear complex receives cutaneous afferent projections from the ipsilateral head, face and intraoral mechanoreceptors which are organized somatotopically in all rostrocaudal nuclear planes (Darian-Smith, et al., 1963; Kurger and Michel, 1962). Marfurt (1981) utilized transganglionic HRP transport to delineate the somatotopic representation of each peripheral sensory branch of the trigeminal nerve (supraorbital, infraorbital, mental, inferior alveolar and corneal divisions). In general, each of these trigeminal branches sent axonal projections to all levels of the sensory trigeminal nuclear complex: main sensory nucleus (Stn), pars oralis (Sto), pars interpolaris (STi) and pars caudalis (spinal trigeminal, STc). The corneal afferents project ventrolateral predominately to STi and STc. Supraorbital, infraorbital, and mental nerve projections terminate ventrolateral, dorsalateral and medial respectively, in STn, STi and STc. The inferior alveolar nerve represented medial most in

sensory trigeminal complex surrounding representation of the mental nerves, projects equally to all levels of the sensory trigiminal complex.

The Stn, STo, STi and STc project axons along the crossed ventral trigeminal tract to the contralateral ventroposteromedial nucleus (VPM) of the thalamic ventrobasal (VB) complex (Mizuno, 1970). These axons join the medial lemniscus after crossing the midline. STn axons also project to ipsilateral VPM, and less so to the intralaminar, centrolateral and centromedian nuclei. These ipsilateral intraoral and perioral projections via the fascicle of Forel will be discussed in later sections (Bombardieri, et al., 1975).

Section 2.2.3.b: Dorsal Column Nuclei in the Monkey

In the rhesus monkey Carpenter (et al., 1968) and Shriver (et al., 1968) described projections of dorsal root primary sensory afferents onto the DCN as follows. Fibers from the upper seven thoracic (T) and cervical (C) dorsal roots project in a somatotopic fashion upon portions of the cuneate nucleus and external cuneate nucleus. Fibers from lower thoracic, lumbar, sacral and coccygeal dorsal roots project somatotopically upon the nucleus gracilis. No fibers from dorsal roots caudal to T_7 project to the external cuneate nucleus. In the cuneate and external cuneate nuclei fibers terminate in horizontal laminar zones from the cervical and first seven thoracic dorsal

roots. These laminae are arranged so that more rostral roots teminate progressively ventrolaterally in these nuclei. C_5 through C_8 terminate in a central core region about which other dorsal roots terminate in oblique serial laminae. Roots of the lumbosacral plexus project to a core region in the gracile nucleus with lower thoracic and upper lumbar dorsal roots in serial narrow oblique terminations lateral to the central core. Sacral and coccygeal dorsal roots forming crescent shaped laminae dorsomedial to the gracile central core (see Figure 2-2).

A similar study of dorsal root rhizotomies in the lesser bushbaby (*Galago senegalensis*) yielded the following findings (Albright, 1978; Albright and Haines, 1978). Generally, somatotopic distribution of terminal fibers is like that described previously for the cat and rhesus monkey. Additionally, afferent projections ascend from coccygeal and sacral dorsal roots to nucleus Z. Forelimb afferent projections from the dorsal roots ascend to the basal cuneate region and medial tongue between the cuneate and external cuneate nuclei at their ventral border. These projections were conjectured to be Group I muscle afferents conveying kinesthetic information toward thalamus.

Kerr (et al., 1968) reported on the somatotopic organization of the sensory trigeminal nuclear complex in the monkey. At all rostrocaudal levels of each trigeminal division (pars caudalis, pars interpolaris,

pars oralis and the main sensory nucleus) ipsilateral head, face and intra oral structures are represented. The mandible is represented dorsolaterally, the orbital area ventrolaterally, the oral cavity is medial to both. Representation of buccal and lingual surfaces was found predominately in main sensory nucleus (STn) of the trigeminal complex. As in the cat, the trigeminal sensory nuclei project predominately to the contralateral ventroposteromedian nucleus (VPM) of the thalamus (Mizuno, 1970). There are perioral and intraoral projections from the STn to the most medial aspect of ipsilateral VPM.

Section 2.2.3.c: Dorsal Column Nuclei in the Raccoon

The somatotopic organization of the DCN in the raccoon was elucidated by investigations of Johnson, Welker and Pubols (1968). Utilizing microelectrode mapping of sensory single unit or unit-cluster activity evoked by natural stimulation of peripheral cutaneous and deep mechanoreceptors, neuronal degeneration studies, Nissl-cytoarchitectonics and myelo-architectonics (myelin staining) the following observations were reported.

The cuneate-gracile complex largely receives cutaneous afferents responsive to gentle stimulation of hairs and glabrous surfaces of the postcranial body, with some input from "deeper" tissues. The external cuneate nucleus and its medial tongue region extending

over and into the cuneate-gracile complex receive afferents exclusively from deeper (e.g. muscle, joints, etc.) tissues. The orientation: head - lateral in the spinal trigeminal nucleus, foot in the gracile nucleus and forelimb/trunk in the cuneate nucleus was demonstrated (see Figure 2-2). Within the cuneate nucleus a central core of glabrous cutaneous digits was mapped. The first digit was ventrolateral in the core the other digits in register extending dorsomedially, each digit representation area corresponding to a condensation of neuronal perikarya (subnuclei or lobules). Between the digit subnuclei laminae of afferent cutaneous sensory fibers projected into the cuneate nuclear subregions. Similar laminae of afferent fibers lay between body representation areas subjacent in the cuneate nucleus, but not contiguous on the body surface (i.e. laminae between tail and foot subnuclei, between trunk and arm, etc.). Dorsal hand is represented dorsal to the glabrous digit subregions, which in turn are dorsal to palm representation. The group of cells forming a medial shell about the glabrous digit subnuclei, in the cuneate nucleus, represented postaxial arm and trunk cutaneous mechanorecption. This blended into hindleg, foot and tail representations lying sequentially more medial in the gracile nucleus. The medial tongue region of the external cuneate nucleus and the basal cuneate nuclear regions received deep arm and hand (kinesthetic) forelimb afferent projections,

preaxial arm, neck and pinna receptor fields stimulated single unit activation in the lateral part of the main cuneate nucleus between the digit 1 representation in the glabrous forepaw core, and the medial edge of the spinal trigeminal nucleus.

Section 2.2.4: Cutaneous and Kinesthetic Second Order Neuronal Projections to the Ventrobasal Complex and Other Thalamic Nuclei

Recently Berkley (1980) compared projections to the lateral diencephalon from the three sensory components of the medial lemniscus (DCN-lemniscal, spino-cervico-lemniscal and spinothalamic), in both cats and monkeys. A double orthograde labelling technique was utilized, combining autoradiographic examination of one component of the medial lemniscus, with an axon terminal degeneration technique in another component. In this manner the diencephalic projections of two components of the medial lemniscus could be compared directly in the same animal. The input of the medial lemniscus in both species is arranged in a dense core-like fashion, the core consisting of projections to the ventrobasal nuclear complex (VB), surrounded by a less dense shell of projections to adjacent thalamic nuclei. This "nuclear shell" consisted of the posterior group (PO), ventroposterior inferior nucleus (VPI), the border region between VB and the ventrolateral nucleus (VL).

This latter border region receives kinesthetic input and will be called kinesthetic VB (KVB). In addition to the lateral diencephalic nuclei receiving somatic sensory input, the medial geniculate magnocellular division and caudomedial zona incerta also receive mechanosensory projections.

The study by Berkley (1980) showed VB receives dense inputs from the DCN, the lateral cervical nucleus (LCN) and the spinal trigeminal nucleus (STc) in the cat. In the monkey there is a major spinothalamic (ST) component in addition to projections from DCN, LCN and STc. There is some convergence of the axonal terminations from the various projectional pathways in the nuclear shell region. Virtually complete segregation (nonconvergence) of the axonal projections from LCN, DCN and ST was noted as they project to preferred territories within VB where their respective terminations are densest. The terminal field of each pathway tends to be clustered with regions of dense terminations, separated by termination sparse regions. Different parts of the shell region receive sparse input from pathways projecting more densely in the adjacent ventroposterior nuclear core.

The projections from the DCN to VB are confined to VPL (Berkley, 1980; Kalil, 1980). The gracile nucleus projects to lateral VPL, the cuneate nucleus to medial VPL. These projections overlap in the middle of VPL. In Berkley's (1980) studies of medullary projections to

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VB, the nucleus Z, basal cuneate, external cuneate nucleus medial tongue region and ventral cuneate nucleus were found to project axons to an anterodorsal nuclear shell region capping VB, in the cat. This anterodorsal nuclear cap is the thalamic relay nucleus of kinesthetic information (KVB) to cerebral cortex, being located: between VPL and VL rostrally, between VPL and ventroposterior medial (VPM) dorsally, and between VPL and the lateral geniculate nucleus laterally.

The sensory trigeminal nuclear complex projects to contralateral VPM from all rostrocaudal levels by the way of the ventral trigeminal tract, in both the cat and monkey (Mizuno, 1970). As these trigeminal projections cross the midline, they join the medial lemniscus on its way to VB. The principle sensory trigeminal nucleus also sends ipsilateral projections to the medial most portion of VPM, as well as the intralaminar, centromedian and centrolateral thalamic nuclei (Mizuno, 1970). The ipsilateral projections travel rostrally via the dorsolateral trigeminal tract to VPM.

The somatotopic representations of the body surface in cats and monkeys is depicted with hindlimb and foot laterally in VPL, forearm and neck medial in VPL and the head in VPM. The principle trigeminal nucleus also sends ipsilateral projections medial most in VPM, in both monkeys and cats (Mizuno, 1970).

In the cat's caudal diencephalon the LCN and ST, but not the DCN and STc, project to PO and MCMm. LCN also projects throughout VB but predominately lateral and dorsal to it. ST projections were concentrated medially in VB. All three pathways (DCN/STc, LCN and ST) project to the zona incerta. There are scattered inputs to the kinesthetic VB (KVB) anterodorsal shell by LCN and ST. In the monkey, there is a small component of axonal projections from the LCN to VPI, VPM, PO and sparsely within dorsal VPL. LCN projects predominately to the ventral portion of VB in the monkey. ST projections to VB in the monkey were much more dense than seen in the cat. In both species LCN projections were segregated from DCN and ST afferent inputs.

A somatotopic distribution of cutaneous mechanosensory afferents to VB in the cat and monkey were mapped using single unit microelectrode recording (Mountcastle and Henneman, 1949; 1952). In both cases contralateral body representation depicts a crouched figure with its foot and hindquarters pointed laterally and with its body, forelimb and face successively more medially. Distal limbs are located ventrally, proximal limb's and body dorsally. All this within the VB complex (Figure 2-3). There is an expanded ventral volume of VB devoted to glabrous forepaw representation proportional to peripheral cutaneous innervation density.

Figure 2-3:

Illustrated are transverse sections of the thalamic ventrobasal complex (VB) in three species. Microelectrode mapping studies of central nuclear representation have revealed somatotopic organization in transverse section of mid-VB to be similar in all three species. Drawings are extrapolated from electrophysiologic studies in: cat - Mountcastle and Henneman, 1949; monkey - Mountcastle and Henneman, 1952; raccoon - Welker and Johnson, 1965. Abbreviations of thalamic nuclei: ventroposteromedial (VPM), ventroposterolateral (VPL), ventroposterior inferior (VPI), ventrolateral (VL), centromedial (CM), lateral geniculate body (GLD), laterodorsal (LD); cerebral peduncles (CP) and third ventricle (V-III).

With respect to medullary kinesthetic projections to the diencephalon in the cat, the findings of Berkley (1980) are in agreement with those previously described by Bovie (1970). The kinesthetic projections from nucleus Z (Nz) course similarly to the internal arcuate fibers, cross the midline at the mid-olivary nuclear level, travelling in the medial subdivision of the medial lemniscus. These fibers terminate in an area extending from the rostral pole of the lateral geniculate body, in a strip lying in the dorsal transitional region between VPL and VL (termed the VPL-VL transition zone but more recently defined as kinesthetic VB, KVB) (Grant, et al., 1973). Microelectrode mapping studies of KVB demonstrated activity of this diencephalic region was evoked by stimulation of Group I muscle afferent projections in the cat (Anderson, et al., 1966; Rosen, 1969b; Mallart, 1968). The above mapping studies also reported Group I projections to VPL proper. The rostrolateral pole of VPL receives afferent input from mechanoreceptors in joints (Yin and Williams, 1976).

In the monkey lesions of the external cuneate nucleus (ECu) result in terminal degeneration within the KVB transition zone, between VPL and VL at their rostral extent (Bovie and Bowman, 1981). Microelectrode mapping in VB of monkeys demonstrated Group I muscle afferent responses evoked from contralateral forelimb were localized in a narrow rostral cap over VPL (Maendly,

et al, 1981; Jones and Friedman, 1982). These latter studies reported convergence of input from muscles which all acted in an agonistic manner at a particular joint.

The word convergence when used in this thesis implies that the electrophysiologically recorded response of evoked units at a given stereotactic location of the recording micro-electrode were driven by anatomically disjoint (but functionally grouped) receptive fields. Kinesthetic information from adjacent muscles acting similarly at a joint converge into a common receptive field. The units driven by a kinesthetic receptive field may also respond to (display convergence of information from) fascial and cutaneous mechanoreceptive fields affected by the muscular action.

Dykes (et al., 1981) reported cutaneous submodality segregation in the squirrel monkey with pacinian receptor responses in the ventroposterior inferior nucleus (VPI), cutaneous rapidly adapting and slowly adapting responses in VPL and VPM. "Deep" (kinesthetic) input was to a dorsal cap over VPL and VPM (KVB).

To examine the issue of convergence of cutaneous and kinesthetic inputs to KVB in the monkey Jones (1983) injected horseradish peroxidase (HRP) into individual medial lemniscal axons to study their axonal termination patterns. In his sample of only 27 axons he found as many lemniscal axons projected to KVB as projected to

both KVB and VB proper (5 axons to each). The majority of lemniscal axons projected into VB proper alone. The termination of the lemniscal axons was discrete, not spread along a rostrocaudal orientation as is reported in somatotopic and submodality mapping studies of sensory thalamus.

In their investigation of the DCN of the raccoon Johnson, Welker and Pubols (1968) reported the following observations on the afferent projections from the medullary nuclei. Transection of the medial lemniscus caused cell shrinkage in the contralateral cuneate-gracile nuclei but not the ECu or its medial tongue (MT) region. Ablation of ipsilateral cerebellar peduncles caused degeneration of cells in the ECu. Only ablation of the medial lemniscus and ipsilateral cerebellar peduncles caused cell degeneration in the MT region.

To further determine the source of medullary projections to KVB Ostapoff (1982) injected HRP into KVB or ipsilateral cerebellar cortex receiving muscle afferent projections. Both injection sites were identified by evoked activity during microelectrode recording. Ostapoff (1982) reported the following: 85-95% of cells in the reticular portion of Nx and also in Nz project to contralateral KVB, as do 20% of cells in the basal cuneate nucleus, ECu, rostral cuneate and MT. Projections to ipsilateral cerebellar cortex comprise 30% of Nx compacta, 70% of MT cells, 20% of cells in the rostral

cuneate and ECu. Electrophysiologic evidence confirmed all these medullary regions as receiving "deep" sensory afferent input. Injections of HRP in medial KVB labelled Nx reticular, basal cuneate, medial ECu and MT. Injections into rostrolateral KVB labelled similar medullary nuclear regions plus the rostral cuneate-gracile pole. Little or no overlap of labelling within medullary nuclei occurred from the medial and lateral KVB HRP injections.

The raccoon may be more like the monkey in the medullo-thalamic kinesthetic projections, than is the cat. The only kinesthetic projections from the medulla which have been identified in the monkey course from the ECu to KVB (Berkley, 1980; Bovie and Bowman, 1981). Projections from ECu to KVB have never been described in the cat. In the study by Ostapoff (1982) 20% of the cells in ECu projected to KVB in the raccoon.

Wiener (1983) recorded single-unit and unit-cluster evoked responses in an extracellular microelectrode mapping study of raccoon VB and KVB. A distinct zone of kinesthetic projections was found in the rostral and dorsal aspects of VB responding to "deep" mechanosensory stimulation. The kinesthetic responses were somatotopically organized with axial structures dorsal, distal limb ventral, all this overlaying a core of cutaneous responses in VB proper, with its expanded glabrous forepaw representation. The cutaneous mechanosensory representation of VB of the raccoon elucidated by Wiener's (1983) study

was largely in agreement with that previously reported by Welker and Johnson (1965).

Welker and Johnson (1965) systematically explored VB in the raccoon. They compared Nissl and myelin cytoachitectures within VB, with responses recorded in microelectrode mapping studies evoked by somatic sensory stimulation. Discreet ablations within S-I and lemniscal transsection were also utilized to study subsequent retrograde changes within VB. Subnuclear organization within VB of the raccoon into discreet lobules were described as being best delineated in myelin stained sections. Electrophysiological activity evoked within each subnucleus (lobule) of VB was in response to stimulation of individual contralateral glabrous forepaw digits, the hindlimb or head. No overlap was found in the thalamic representation of body parts that are actually separated from one another at the periphery, within a subnuclear lobule. In the horizontal plane glabrous digit representation is anterior most within VB, caudal to this is glabrous palm, caudal to this is the torso, medial to the digits is head and lateral to the digits is hindlimb. In the transverse plane torso representation is dorsal to glabrous palm, which is dorsal to the glabrous digit representation area. Again, head is medial and hindlimb lateral to the digit representation area (see Figure 2-3). Dorsal cutaneous digit responses are located vental most within VB. The forelimb digits occupy an expanded region of

VB with the first digit representation medially and the others in register more laterally between the head and hindlimb representations in both the transverse and horizontal planes. The fibrous laminae, which give raccoon VB its lobulated appearance, are of medial lemniscal origin which project to penetrate and ramify within the VB subnuclear regions. Similar lobules were reported in the DCN of raccoons separated by afferent fibers of the dorsal columns (Johnson, et al., 1968).

Welker (1973), in his discourse of eighteen principles of structural and functional organization of the ventrobasal complex, listed subnuclear organization with separation by laminae of afferent axons as a general organizational feature of VB in mammalian species. The expanded nuclear subregions representing locales of high peripheral receptor density (e.g. rhinarium and forepaw glabrous digits) serve to preserve the relative size of the smallest receptor fields in a representation of projections from specialized body regions most utilized by a species in tactile discrimination behaviorally. There is preservation and segregation of mechanosensory submodalities as they relay to and from VB. The following subsection examines the cortical representation of kinesthetic and cutaneous mechanosensory information and its thalamocortical origin in the cat, monkey and raccoon.

Section 2.2.5: The Body Representation Areas Within Somatic Sensory Cortex of Monkey, Cat and Raccoon

The historical electrophysiologic mapping studies of S-I cortex by Adrian (1943; pig, sheep, horse, and other ungulates), Woolsey and Fairman (1946; pig, sheep and other mammals), Mountcastle (1957; monkey) and Welker and Seidenstein (1959; raccoon) elucidated the principle that gyral topography was related to predictable behavioral specialization in tactile exploration of the environment. J.I. Johnson, Jr. (1980) called this principle of mammalian speciation the "New Phrenology". In all mammalian species studied with well developed neocortices, sulci have formed in S-I between representation areas of the major tactile surfaces used by the species in question (e.g. hindlimb, body, forepaw digits and face in the raccoon; hindlimb, body, maxilla and mandible in ungulates).

These above studies also lead to the traditional concept that a single representation of body surface was located in the primary sensory area (cytoarchitectonic areas 3, 1 and 2 in primates) along with post-central gyrus. S-I and the primary motor are (M-I) were recognized to be separated by the central sulcus, with M-I (cytoarchitectonic area 4 in primates) located along the pre-central/post-cruciate gyral crown.

More recently, it has been shown that as many as four representations of the body surface exist in the S-I area of primates (Merzenich, et al., 1978; Kaas, et al., 1979; Nelson, et al., 1980; Sur, et al., 1982). Each cytoarchitectonic field (3a, 3b, 1 and 2) receives submodality specific mechanosensory information with little convergence at field borders. Area 3a receives kinesthetic information from rapidly adapting muscle afferents. Area 3b is regarded as "S-I proper" receiving rapidly adapting cutaneous mechanosensory inputs. Area 1 receives information from slowly adapting cutaneous mechanoreceptors. Area 2 receives mechanosensory information from joints.

One popular theory of cerebral cortical organization first proposed by Mountcastle (1957) depicts S-I cortex as a mosaic of cylindrical columns oriented perpendicular to the cortical surface through all six layers. Mountcastle (1978) has further refined his description of S-I cortical columns specifying their diameters at about 30 m minicolumns assembled into functional aggregates of ten- to one hundred-fold larger diameter. This principle derived from the observation that as a microelectrode penetrates S-I cortex perpendicular to the cerebral surface, evoked single-unit potentials from the same receptive field in the periphery to all 6 cortical layers is observed. The cortical columns of S-I receive

projections from discrete rostrocaudal lobules of cells in VB (Kosar and Hand, 1981).

All thalamocortical axons leaving VB on one side of the midline reach ipsilateral cerebral neocortical fields. The receptive fields represented in the VB thalamocortical projections are activated predominately by contralateral body surfaces in primates and carnivores (see Welker, 1973). These same VB projections represent proportionately more ipsilateral peri-oral and intra-oral receptive fields in artiodactyla (Cabral and Johnson, 1971). Bombardieri, Johnson and Campos (1975) found a large proportion of ipsilateral oral and a small portion of contralateral oral receptive fields in VB among three mammalian descendents of palaeoryctoid insectivores (cats, raccoons, and sheep). They reported other therian mammals (oppossums, agoutis and squirrel monkeys) had little or no ipsilateral intra-oral representation within VB. The sources of these projections were reported to lie in the ipsilateral main sensory trigeminal nucleus in the cat and monkey (Miuno, 1970). Ipsilateral and bilateral body representation have been reported in hedgehog (Erickson, et al., 1964) and oppossum (Erickson, et al., 1967) within a small portion of VB.

In the succeeding subsections body representation within S-I and the second somatic sensory area (S-II), and their thalamic origin, are compared in the monkey,

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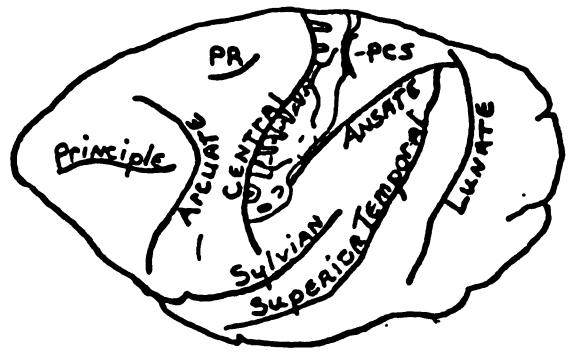
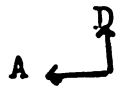
cat and raccoon. Contralateral callosal projections are not discussed.

Section 2.2.5.a: Somatosensory Cortex in the Monkey

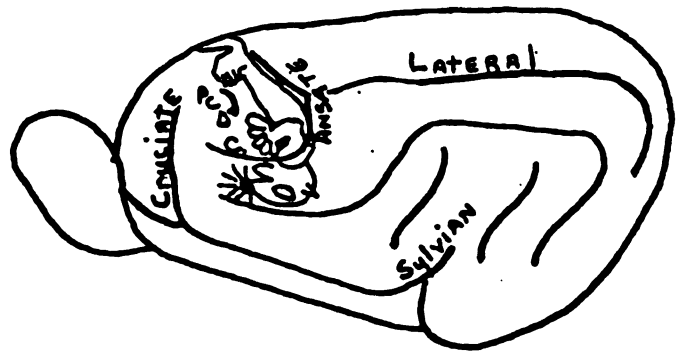
Primary somatosensory cortex (S-I) previously had been thought to contain a single somatotopic representation of the cutaneous body surface in almost all species (see Figure 2-4). Recently the discovery of four separate somatotopic representations in S-I of monkeys, oriented in mediolateral belts corresponding with the four cytoarchitectonic fields (areas 3a, 3b, 1 and 2), has altered the historic view of S-I organization (Merzenich, et al., 1978; Kaas, et al., 1979; Nelson, et al., 1980; Sur, et al., 1982). Areas 3b and 1 contain representations of cutaneous mechanosensory receptive fields, while areas 3a and 2 contain representations of "deep" receptive fields. Generally all somatic representations are oriented with caudal peripheral body lying medially on postcentral cortex, and rostral body and face located laterally (see Figure 2-4). Areas 3b and 1 contain mirror image representations of body surface in monkeys (Merzenich, et al., 1978; Kaas, et al., 1979; Nelson, et al., 1980; Sur, et al., 1982). These representations are organized in parallel with tail located medial, and head lateral. The representations of hairy skin on the face, arm, trunk and leg in areas 3b and 1 are reversed in old world monkeys (cebus and squirrel) as compared to new

MONKEY





CAT



RACCOON

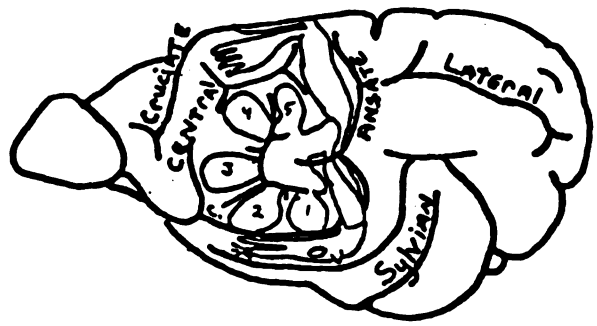


Figure 2-4: Illustrations of the left cerebral cortical surfaces in three species. The somatotopic distribution of cutaneous mechanosensory projections to the postcentral cortex is drawn onto the cortical surface (fashioned after: monkey-Jones and Powell, 1969a; cat-Mountcastle, 1957; raccoon-Welker and Seidenstein, 1959). Sulcal abbreviations: superior precentral (PR), postcentral (PCS), coronal (C).

world monkeys (owl and macaque) (Sur, et al., 1982). Regions representing the same receptive fields in areas 3b and 1 receive thalamocortical projections from the same regions of VB (Nelson and Kaas, 1981). Area 3b is considered S-I proper and is oriented with digit representation pointing rostrally into the central sulcus. The medial digits represented laterally to their more lateral members. In area 3b of old world monkeys (cebus and squirrel) leg, arm trunk and face have dorsal hairy body surfaces represented anteriorly to adjacent ventral body surfaces (Sur, et al., 1982). This order of body part representation is reversed in area 3b of new world monkeys (owl and macaque) with dorsal body surfaces represented posterior to ventral body surfaces in S-I.

Neurons in area 2 are principally responsive to rotation of the joints, and stimulation of periosteum and fascial planes. Area 1 neurons respond to rapidly adapting cutaneous receptors, area 3b neurons to slowly adapting cutaneous receptors. Area 3a neurons receive information from muscle afferent projections and other "deep" receptive fields (Mountcastle and Powell, 1959; Phillips, et al., 1971; Wiesendanger, 1973; Paul, et al., 1975; Tanji, 1975; Heath, et al., 1976). Powell and Mountcastle (1959) first suggested that afferent fibers relaying from single dorsal roots relate to a narrow rostrocaudal band across all of S-I architectonic fields. Neurons at the same mediolateral level in the separate

architectonic fields represent similar body surface location (Werner and Whitsel, 1968; Pubols and Pubols, 1971, 1972), but respond to modality specific receptive fields.

Group I muscle afferent responses have been recorded in areas 3a and adjacent area 4 (primary motor cortex, M-I), in response to ramp-stretch of hindlimb muscles (Hore, et al., 1976; Wise and Tanji, 1981). Muscle afferent input to caudal area 4 was both dynamic (primary spindle afferents) and static (primary and secondary spindle afferents) in responsivity, while rostal area 4 responded only to dynamic ramp stretch. Area 3a showed a response amplitude which correlated well with muscle stretch velocity as compared to area 4. Area 4 also receives cutaneous mechanoreceptor input in the caudal part adjacent to area 3a, while area 3a was found to receive no cutaneous input in this study (Tanji and Wise, 1981).

The second somatic sensory area (S-II) in the monkey was previously described as lying on the anterior supra-sylvian gyrus and in the suprasylvian sulcus (Rose and Mountcastle, 1959). Jones (1975) examined thalamocortical connectivity to this area and concluded the term S-II should be reserved for the cortex in this region which receives projections from the thalamic ventroposterior nuclei (VPL and VPM). Robinson and Burdon (1980a) determined a detailed map of S-II proper in awake monkeys. Digit 1 is located medially, digit 5 laterally

and the other digits in register between with slightly overlapping representation. About 66% of the units recorded were evoked from contralateral digits while 34% were from bilateral projections. Trigeminal projections were predominately bilateral and located anterodorsal to the hand and digit projections. Leg and foot representations are caudal to forelimb, and axial body is dorsal.

Evoked somatic sensory responses can also be recorded in several areas adjacent to S-II proper: area 7b, retroinsular, postauditory, and granular insular cortex (Robinson and Burton, 1980b). Receptive fields for area 7b and granular insular cortex were large and bilateral (Robinson and Burton, 1980c). No somatotopic organization was apparent in granular insular cortex. Area 7b possessed crude somatotopy with head represented medially, body and hindlimb laterally. Both posterior auditory and retroinsular cortices showed convergence of auditory and cutaneous mechanosensory input. The mixed modality sensory projections to cortex adjacent to S-II proper (Jones, 1975) have long confused the somatotopic organization of S-II (Robinson and Burton, 1980a).

Section 2.2.5.a.i: Thalamocortical and Intracortical Connectivity of S-I and S-II in the Monkey Cerebral Cortex

Lesions of the ventroposterior nuclei (VPL or VPM) cause axon terminal degeneration in areas 1, 2 and 3 as

well as S-II. The degenerating fibers are of larger diameter in area 3 than those in areas 1, 2, and S-II, as well as more numerous in area 3b than any of the other S-I fields (Jones and Powell, 1969b). Terminal degeneration was concentrated in layer IV of each cortical area. Lesions in VPL cause heaviest terminal degeneration in middle area 3b, lesions in VPM affecting terminals in lateral area 3b predominantly; with corresponding degeneration in S-II areas representing the head and forelimb respectively. Reciprocally, lesions in medial postcentral gyrus cause terminal degeneration in lateral VPL extending into the adjacent zona incerta, and lateral lesions in the postcentral gyrus leads to axonal degeneration in VPM. Lesions in S-II show the same pattern of corticothalamic axonal degeneration in VPL and VPM, mostly in the ventrum of these thalamic nuclei. The cutaneous core region of S-I (areas 3b) receives thalamocortical projections from central cutaneous core zone of VPL and VPM, while area 3a receives input from the anterodorsal cell zone over VPL (Whitsel, et al., 1978; Maendly, et al., 1981; Jones and Friedman, 1982; Jones, et al., 1982). Areas of VPL core situated dorsal, ventral and posterior in the central cutaneous zone project to areas 3b and 1 (Nelson and Kaas, 1981). The VPL-VL (KVB) transition zone projects to areas 3a and 2, while anterior VPL-VL shell projects to area 3a exclusively. The somatosensory cortical areas

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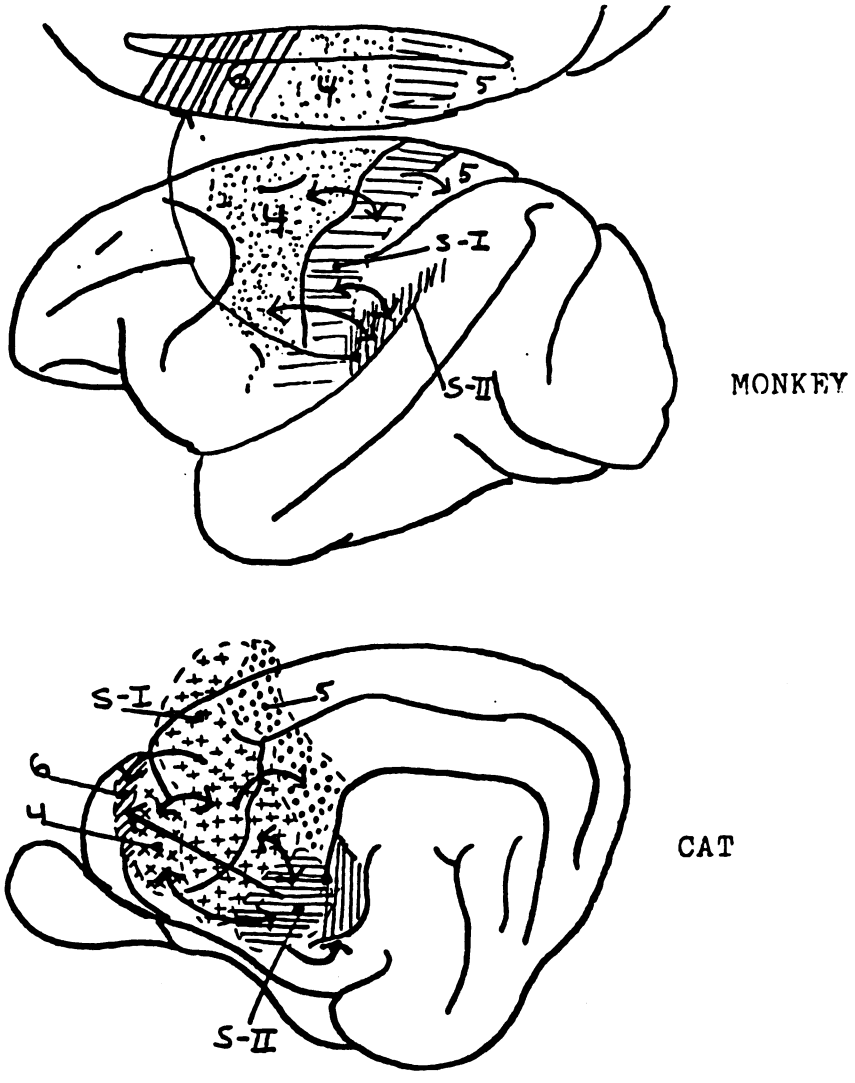
around S-II proper are thought to receive projections from the posterior thalamic nuclei such as ventroposterior inferior n. and the magnocellular division of the medial geniculate body (Jones and Friedman, 1982; Jones, et al., 1982).

Regarding intracortical connectivity, area 3b projects to areas 1 and 2. Area 1 is reciprocally connected with areas 3a, and area 2 reciprocally connected with area 4 and parts of area 5. S-II receives axons from areas 3a, 4, 1, 2 and 5 (all parts) and projects back to areas 3a, 4 and 5 (Jones, et al., 1978). Two types of intracortical connections were seen in the above study. Non-specific connections whose axons spread indiscriminately across cytoarchitectonic borders terminating in all cortical layers except layer IV. Specific connections ramifying in narrow mediolaterally oriented strips in layers I-IV of specific cytoarchitectonic fields. These results largely agree with those previously reported (Jones and Powell, 1969a) as depicted in Figure 2-5. Unit cluster responses to cutaneous stimulation recorded in area 4 may be elicited via projections directly from S-II or possibly from connectivity of area 3a to area 2 to area 4. Muscle afferent responses in area 4 may be evoked via projections from area 3a to area 2. Other alternative intracortical pathways may be possible in the connectivity above. A direct pathway from area 3a to area 4 has been demonstrated electrophysiologically (Zarzecki, et al.,



2-5: An illustration of ipsilateral intracortical connectivity in the monkey (Jones and Powell, 1969a) and cat (Jones and Powell, 1968). Projections within S-I (areas 3a, 3b, 1 and 2) are not distinguished.

1978) in cats. Wiesendanger (1973) felt that Group I muscle afferents reach motor cortex by way of intra-cortical relay due to the longer latency of evoked responses in M-I as compared to S-I.

The distinctive cytoarchitecture designating area 3a can only be seen in the post-cruciate dimple cortical area of the cat, and the anterior bank and fundus of the central sulcus in monkeys (Jones and Porter, 1980). This cytoarchitectonic area is described as the cortical region where the attenuated internal granular layer (IV) of area 3b extends rostrally to overlie the caudally extending layer V giant pyramidal cells (Betz cells in primates) of motor cortex.

In the rhesus macaque, the portion of area 3a which receives hindlimb muscle afferent projections corresponds to the caudal extent of the layer V Betz cells without a concommitant layer IV granular layer present (Jones and Porter, 1980). In primates where area 3a was originally defined cytoarchitectonically, the criteria given this area is only rigidly met in the region of forearm muscle representation. The strict definition of a cytoarchitectonic field as a region of cortex in which major cytoarchitectural features are relatively constant (all parts share the same basic pattern of cortical layering) and in which all parts share the same pattern of input and output connectivity is not met by area 3a in one of the species in which it was originally defined.

In the raccoon no overlap of the attenuated layer IV cells and giant pyramidal cells of layer V could be found histologically (Johnson, et al., 1982). Group I muscle afferent responses could be evoked on the anterior bank of the central sulcus in this species. This prompted Johnson and his co-workers to suggest that an electrophysiologically defined area 3a (a zone of muscle afferent projections) may be more easy to distinguish than a cytoarchitectonic area 3a, in species other than the cat and monkey. They suggested that muscle afferent projections to anterior S-I may be more strictly associated with the area of the central sulcal folding, than with a particular cytoarchitecture (Johnson, et al., 1982). In their study of the raccoon, Johnson and his co-workers did not attempt to define the limits of area 3a to determine if a single (if any) cytoarchitectural feature defined the zone of muscle afferent projections.

Section 2.2.5.b: Somatic Sensory Cortex in the Cat

In the cat mechanosensory submodalities are segregated in S-I forming multiple body representations which are less strictly associated with cytoarchitectonic boundaries in comparison to S-1 in the rhesus monkey (Mountcastle, 1957; Dykes et al., 1980; Dykes and Gabor, 1981; Sretavan and Dykes, 1983). Input from cutaneous receptive fields project to areas 3b and 1, while area 3a receives projections from "deep" forearm and hindlimb

input. A rostrocaudal "deep" to cutaneous gradient was found (Dykes, et al., 1980) as was previously reported in the monkey. The change in sensory modality eliciting responses when going from area 3a caudally toward area 3b was abrupt (within a 100 μm rostrocaudal advance of the electrode), with only 5% cutaneous responses in area 3a and 17% deep responses in area 3b. An abrupt change from slowly adapting cutaneous responses in the caudal half to two-thirds of area 3b, to rapidly adapting cutaneous evoked in the cranial part of area 3b occurred. This submodality segregation was not at the border between areas 3b and 1 as previously reported in the monkey. Three representations of the feline body surface could be ascribed to each of the areas 3a, 3b rostral and caudal 3b/1 (Dykes, et al., 1980; Sretavan and Dykes, 1983). The rostral-most body representation encompasses an ovoid region about the postcruciate dimple containing area 3a and mapping as "deep" forearm mainly, but with the entire "deep" body represented. The other two cortical cutaneous representations lay within crescent shaped areas (caudal and adjacent to the "deep" body representation) in rostral area 3b, and caudal area 3b and 1. Caudal to the postcruciate dimple is hindlimb, tail and abdomen medially; laterally on both sides of the coronal sulcus are thorax, forelimb, neck and head representation areas (see Figure 2-4).

In the cat, the anterior ectosylvian gyrus and adjoining sulci contain several somatic sensory representations defined electrophysiologically, of which the second somatic sensory area (S-II) is the largest (Burton, et al., 1982). Within S-II is a detailed somatotopic map, and a smaller medial zone containing exclusively forelimb and hindlimb in a less precisely organized map. These were defined as S-II because they receive thalamocortical projections from VB (Jones and Powell, 1968; Spreafico, et al., 1981). The major representation region for the apices of the limbs is on the anterior ectosylvian gyrus (Burton, et al., 1982) not along the sulcal wall as previously reported (Carreras and Andersson, 1963; Landgren, et al., 1967). Within the suprasulvian sulcus lies another region where evoked cortical units form a somatotopic map of cutaneous and kinesthetic representation, but in which units may be driven by contralateral auditory stimuli, also (Burton, et al., 1982). This region of convergent cutaneous and auditory afferent input had been previously described by Clemo and Stein (1982), and designated S-IV.

The body representation in feline S-II proper is a cat oriented with head anterior and tail posterior. There is a dramatically enlarged forelimb digit representation with digit 5 medial, digit 1 lateral, the rest of the digits in register between. The hindlimb and foot are caudal to, but oriented similarly to, forelimb and

forepaw representation areas. The axis of proximal to distal limb representation was described as arcuate in a clockwise direction from the center of the paw (Burton, et al., 1982).

Group 1 muscle afferent projections have been shown to evoke activity in the post-sigmoid gyrus and area 3a in electrophysiological studies (Oscarsson and Rosen, 1963, 1965; Oscarsson, et al., 1965; Silfvenius, 1970), as well as near S-II in the deep banks of the suprasylvian sulcus (Landgren, et al., 1967; Silfvenius, 1970). In area 3a there was extensive overlap of cortical representation of individually stimulated severed nerves of muscles, when stimulus parameters were applied which activated only the low threshold Group 1 fibers projecting from one limb. Generally hindlimb lay medial to forelimb on the post-sigmoid crown anterior to the post-cruciate dimple (Landgren and Silfvenius, 1969). Joint afferents from the elbow and knee project to separate locations in each of the areas 1, 2 and 3a with overlap into area 4 (Clark, et al., 1973). All the early experiments of Groups I and II (muscle and joint) afferents by severed nerve stimulation have the possibility of evoking unnatural primary axonal inputs (i.e. not normally evoked by "natural" receptor stimulation) through activating subsets of axons in the severed peripheral nerve (Dykes and Gabor, 1981; Dykes, et al., 1982). There is extensive overlap in the

threshold and frequency of activation of the different axonal groups.

In a study of the awake cat using natural stimulation of Group I afferent axonal input to cerebral cortex, there was a large amount of convergence of information from agonistic muscles in the contralateral forelimb (Rosen and Asanuma, 1973). Forearm muscles which acted similarly at a joint project convergent input to 50% of the single-units recorded from in the post-cruciate dimple area. The other 50% of recorded units responded to a single muscle tendon stretch or movement at the digit, wrist or elbow. All muscle afferent activity recorded in this study was rapidly adapting.

In awake monkeys trained to perform wrist flexion and extension movements, 50% of single-units activated in area 3a were evoked by voluntary shortening of the wrist flexors. The other 50% of recorded units were driven by passive lengthening of the wrist flexors, and a few units driven by passive flexion and extension of the wrist (Yumiya, et al., 1974). These responses were all rapidly adapting, also. Similarly, sinusoidal ramp stretching applied to a single digital extensor tendon elicited activity in area 3a (Lucier, et al., 1975; Murphy, et al., 1975). All studies in which "natural" stimulation (preparations where the peripheral nerves are not severed, responses are evoked by mechanical means) elicit far lower percentages of evoked activity

from Group I muscle afferents outside area 3a and S-II compared to dissected nerve stimulation studies.

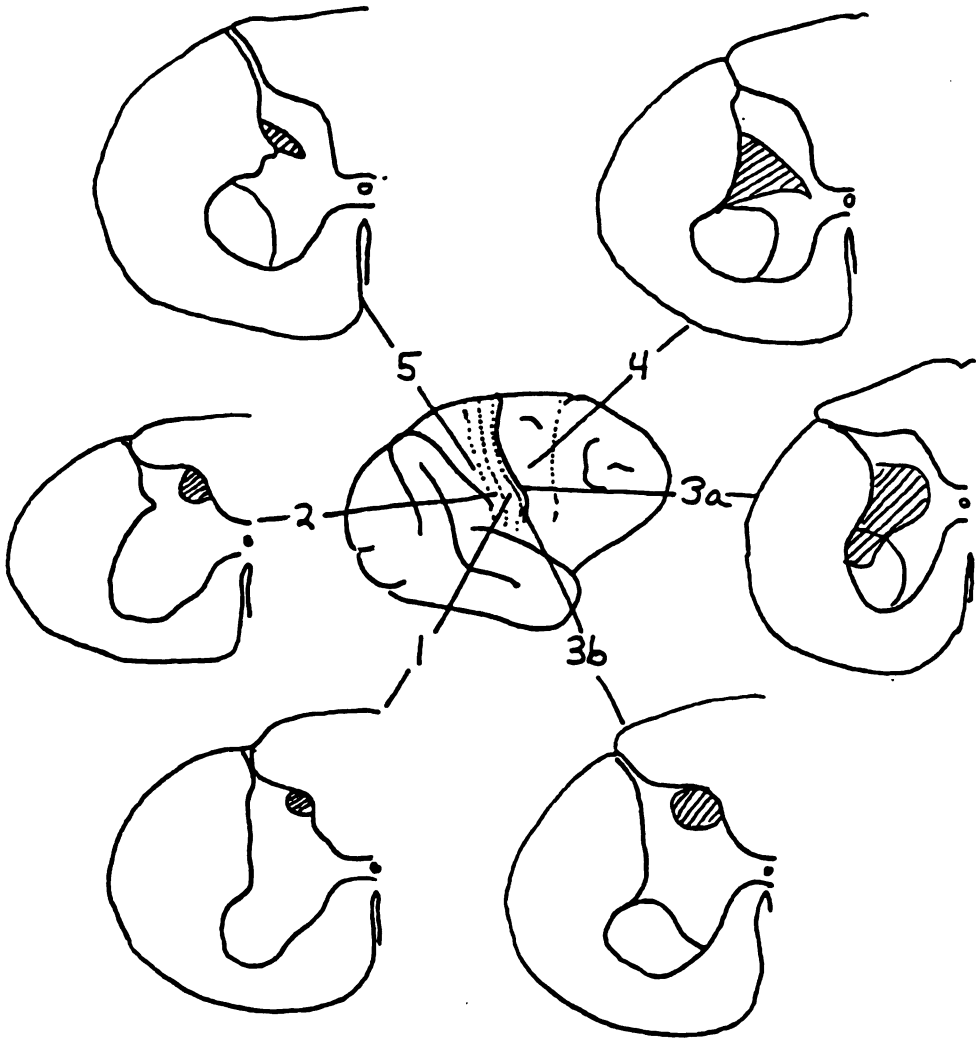
Section 2.2.5.b.i: Thalamocortical and Intracortical Connectivity of S-I and S-II in the Cat Cerebral Cortex (according to the ablation study of Jones and Powell, 1968; 1969c)

Small lesions in VPL give axon terminal degeneration in S-I (areas 3b, 1 and 2), S-II and sparsely in area 3a. Lesions of the rostrodorsal transition zone between VPL and VL (KVB) cause greatest degeneration in area 3a with some in areas 3b, 4 and S-II (Anderson, et al., 1966). Lesions of a discrete location in areas 3a or 3b cause a rostrocaudal band of degeneration across the cytoarchitectonic fields of S-I (Areas 3b, 1 and 2), and degeneration in S-II. Lesions in areas 2 or 1 yielded a diffuse degeneration throughout S-I and sparsely in S-II. This is unlike connectivity reported in the monkey where areas 3a and 3b did not connect reciprocally, and area 3b did not project to S-II. Lesions in S-II reveal projections to rostral S-I and area 4 (as in monkeys where S-II did not project to areas 3b, 1 or 2).

Cortical cells of S-I and S-II project onto sensory relay nuclei in the brainstem. We already know corticothalamic projections are reciprocal to those of thalamocortical origin for a given area of cerebral cortex. Restricted lesions confined to area 3a of cerebral

cortex caused terminal degeneration greatest in the dorsal parts of the dorsal column nuclei (not the cell cluster zones), the basal cuneate and rostral pole of both cuneate and gracile complexes (Kuypers and Tuerk, 1964; Weisberg and Rustioni, 1970. The latter study of HRP retrograde transport displayed a bias of cortioco-bulbar projections toward nuclear subdivisions related to cutaneous afferents from the hindlimb in the gracile-nucleus Z complex and toward nuclear subdivisions related to kinesthetic (muscle afferent) inputs from forelimb within the cuneate nucleus. Nucleus Z receives a sparse population of cortical projections.

The corticospinal projections from each of the cyto-architectonic areas 1-4 in the monkey is shown in Figure 2-6. The major contribution of sensorimotor cortico-spinal projections is from areas 3 and 4 (Coulter, et al., 1976; Coulter and Jones, 1977). Area 3a in this diagram projects to the lateral part of Rexed's laminae 4, 5, 6 and 7 and to lamina 9. Lamina 9 receives group I primary afferent input directly, and contains motor-neurons which innervate muscles of the distal extremities (Kandel and Schwartz, 1981). Input of area 3a to cervical lamina 9 motorneurons in the spinal cord allows cortical influence, presumptively for fine control of motorneuron activity when conscious propioceptive acuity is needed, and to influence distal forearm muscle reflexes. The projections to lamina 7 overlap the area



2-6: Illustration of the differential corticospinal projections from the various cyroarchitectonic fields onto the cervical spinal cord in the monkey. Areas 3a and 4 form the most extensive projections (Coulter and Jones, 1977).

known to contain inhibitory inter-neurons of group Ia afferent reflex arcs (Brown, 1981).

Section 2.2.5.c: Somatic Sensory Cortex in the Raccoon

In an examination of the principle that animals with specialized integumentary structures utilized behaviorally to explore their environment show corresponding specialization of central sensory neuronal organization, Welker and Seidenstein (1959) chose the raccoon as their subject. Their reasoning was as follows (p. 469 of the above study), "...contrasted with carnivores like cats and dogs, the raccoon makes extensive use of its forepaws in the manipulation and tactile exploration of its environment... [they thought this] suggested the possibility of a relatively elaborate representation of the forepaw receptors within the central nervous system." They reported that 60% of S-I in the raccoon was devoted to representation of contralateral forepaw, as compared to 30% and 20% in the cat and dog respectively. Cortical representation of hand was roughly 95% glabrous surface of digits organized somatotopically on an elaborate enlargement of the post-central gyrus. Digit one representation pointed laterally, digit 5 medially with the other digits in register pointing cranially into the posterior bank of the central sulcus. The glabrous palm representation, with pads represented somatotopically was located caudal to the triradiate sulcus which descends

between the digit and the palm representations areas. Facial representation lay along the lateral bank of the coronal sulcus (see Figure 2-4).

A second procyonculus along the inferior bank of the suprasylvian sulcus was designated S-II. S-II had a similarly enlarged glabrous forepaw representation somatotopically organized (Herron, 1978). Submodality segregation within S-I and S-II was not investigated in the above studies in the raccoon.

In an investigation of the anterior border of the digit 4 representatation area in S-I of the raccoon Johnson (et al., 1982) segregated anterior S-I into three distinct zones, based upon evoked single-unit and unit-cluster responses and not strictly upon cortical cytoarchitectonic features (see Figure 9, Johnson, et al., 1982). Area 4 (M-I) is characterized by the presence of layer V giant pyramidal cells in the cortex anterior to the central sulcus. The central sulcus is highly variable between individual raccoons and may be complete or broken into medial and lateral arms by an intervening gyral bridge. Area 3b is identified most easily by its expanded granular layer IV and the outer cell free stripe of Baillarger. Area 3b receives pure cutaneous mechanosensory information organized somatotopically. Between areas 3b (S-I proper) and Area 4 (M-I) lies an area of cortex which can be further

subdivided by evoked activity, but not cytoarchitectonic criteria, into a zone of "deep" (muscle afferent) projections, and a representation area of mixed submodalities and disjoint receptive fields called the heterogenous zone (HZ) by Johnson and co-workers. The raccoon muscle afferent projection area lay along the portions of the anterior banks and fundus of the central sulcus explored in this study, and did not have the cytoarchitectonic criteria of Brodmann's area 3a. Raccoon area 3a was histologically described as lying anterior to the attenuated cranial end of the cell free stipe, with no apparent relationship to the layer V giant pyramidal cells. Johnson (et al., 1982) suggested an association of muscle afferent projections with the region of the anterior bank of the central sulcus as opposed to a strict association of muscle afferent projections with a particular cytoarchitecture in this species. Similarly, not all of electrophysiologically mapped M-I corresponds with cytoarchitectonically identified area 4 in the raccoon (Harden, et al., 1968).

The raccoon Hz units are evoked by stimulation of discontinuous cutaneous receptive fields (e.g. multiple distal digit responses) of the contralateral forearm. These responses were recorded in the area of the gyral bridge which separates the central sulcus into two arms. While not distinctly somatotopic, the representation of body surface in the HZ is roughly a mirror-image to that

found adjacent in S-I. The cytoarchitectural features of the HZ distinguish it as part of area 3b.

The exquisite somatotopy of thalamocortical projections to S-1 in the raccoon were demonstrated by Welker and Johnson (1965) using discrete cortical ablations in S-I. Ablation of the digit 5 representation gyrus in S-I caused degeneration of cell bodies in the lateral core of VB where evoked digit 5 responses had been mapped. In their study all digits, head tail and hindlimb cortical ablations were individually performed to completely delineate the somatotopy of thalamocortical projections. Herron (1983) demonstrated the same thalamocortical connectivity using HRP retrograde transport. Herron reported the ventroposterior inferior nucleus projected preferentially to S-II along with minor contributions from the centrolateral, centromedian and parafascicular nuclei of the thalamus.

Herron (1979) described the intra- and interhemispheric connections of S-I and S-II in raccoons utilizing single injections of an HRP/tritiated amino acid cocktail or an axonal degeneration technique to examine both afferent and efferent connectivity of these cortical areas. Intra-hemispheric afferents were divided into homotypic (projected to a cortical area which represented a similar body surface receptive field) or non-homotypic. Generally, reciprocal connectivity was demonstrated ipsilaterally between homotypic areas of S-I and S-II.

Section 2.2.6: Summary of the Literature Review

Cutaneous and kinesthetic sensations follow parallel but distinct pathways from mechanoreceptors in the periphery to unique primary somatic sensory areas. Cutaneous sensations begin in integumentary mechanoreceptors and project via dorsal root ganglia into the spinal cord proper or to the dorsal column nuclei. From these locations cutaneous somesthesia is conveyed to the contralateral ventrobasal complex of the thalamus (neglecting some trigeminal contributions of peri-oral and intra-oral receptive fields) along three distinct pathways all contained within the medial lemniscus: the spinothalamic tract, the spino-cervico-lemnisco-thalamic tract and the dorsal column-lemniscothalamic tract. The spinothalamic tract is more highly developed in primates than in carnivores, while the converse is true of the spino-cervico-lemniscothalamic tract. From the ventrobasal complex cutaneous sensation projects along efferent axons to ipsilateral primary somatic sensory cortex (areas 3b and 1 in primates and the cat). At each nuclear relay station toward cortex, somatotopy of information is maintained as has been demonstrated in both electrophysiologic studies and selective axonal projection studies. There is a correlation between central sensory nuclear receptive field size, density of peripheral mechanoreceptors and behavioral tactile

discrimination of the environment. Integumentary areas used to explore the environment have relatively greater mechanoreceptor density and are represented in proportionately larger central sensory nuclear volumes and topographical areas of primary somatic sensory cortex.

Kinesthetic information projects from mechanoreceptors in muscles, tendons, ligaments and joints via dorsal root ganglia to medullary regions which differ in the cat and monkey, enroute to kinesthetic cortex (cortex just anterior to the primary somatic sensory area). In the cat kinesthesia is conveyed via the basal cuneate, rostral dorsal column nuclear poles, nucleus X and nucleus Z to an anterodorsal thalamic nuclear shell which caps the ventrobasal complex. In the monkey kinesthesia is conveyed via the external cuneate nucleus to an anterodorsal thalamic nuclear shell which caps the ventrobasal complex. In the cat the external cuneate nucleus projects exclusively to the ipsilateral cerebellar cortex. The medullary sources of kinesthetic projections in the raccoon are similar to both the cat and monkey originating from: the basal cuneate nucleus, Nucleus X reticular, Nucleus Z, the medial tongue region of the external cuneate nucleus and 20% of the cells in the external cuneate nucleus proper. All these medullary areas project to an anterodorsal kinesthetic thalamic nuclear shell which caps the ventrobasal complex.

In the cat and monkey the kinesthetic thalamic nuclear shell projects to area 3a, located in the area of the post-cruciate dimple or anterior bank and fundus of the central sulcus, respectively. Area 3a though originally defined in primates demonstrates its distinctive cytoarchitecture only in the area of the hand representation area in monkeys. In cats area 3a meets the criteria of a cytoarchitectonic field in its constancy of cytoarthitectural and functional features. In the racoon kinesthetic cortex has been partially described on the anterior bank of portions of the central sulcus where the cytoarchitectonic criteria of area 3a are not met.

SECTION 3: PROPOSED RESEARCH AND ITS RATIONALE

There are several aspects of the organization of the muscle afferent representation zone located anterior to S-I in the raccoon, which were not addressed by the study of Johnson (et al., 1982). These are central to the following series of objectives proposed as the subject of this thesis research:

1. To define the electrophysiological extent and boundaries of the muscle projection zone anterior to S-1 in raccoons.
2. To examine the topological organization of kinesthetic cortical activity recorded anterior to S-1, evoked in response to mechanical stimulation of muscles in the dissected forelimb and hindlimb of the raccoon.
3. To utilize 100 Hz small (<1 mm) amplitude vibratory stimulus applied directly to muscles of the dissected limbs to identify areas of kinesthetic cortex receiving primary muscle spindle afferents.
4. To examine the cytoarchitecture of the entire extent of the zone mapped as receiving muscle afferent information for any unifying characteristics(s) or distinctive cortical layering.

The objectives of this research were to examine the extent, topological organization and cytoarchitecture of the raccoons' cortical area representing muscle afferent projections, between S-1 and M-1. The rationale for performing this research was to help define kinesthetic cortical areas in the raccoon. In this way, kinesthetic cortex may be reinforced as a general organizational feature of cortical body representation in sensorimotor cortex. The previous literature review discussed the somatotopic and cytoarchitectural organization of area 3a in the cat and monkey. In the raccoon, somatotopy in the kinesthetic cortical area has not been demonstrated. Though Johnson (et al., 1982) could not assign the cytoarchitectonic criteria of area 3a to this muscle afferent representation zone, the entire extent of kinesthetic cortex was not determined and so it could not be histologically analyzed in its entirety. The ambiguities of evoking muscle afferent ("deep") activity through the skin when defining a central kinesthetic representation area, leave a doubt as to the mechano-receptors which are giving rise to recorded afferent volleys. By more directly stimulating primary muscle spindles with a submodality selective stimulus in a dissected preparation, little doubt is left as to the mechanoreceptors being perturbed.

The kinesthetic area of S-I is of interest because lesions of Area 3a in humans are known to relieve

symptoms of Parkinson's disease as well as other conditions of postural and intention tremors (Narabayashi and Ohye, 1980). The physiological basis of intention tremor alleviation by this type of clinical intervention is not presently understood. As more information is accumulated about the afferent connectivity of this kinesthetic cortical area perhaps the clinical applications of lesions in area 3a will become apparent.

SECTION 4: ELECTROPHYSIOLOGICAL AND HISTOLOGICAL METHODS OF INVESTIGATION

Unit-cluster cortical activity was recorded as opposed to single unit recording in this study. Unit-cluster recording has the advantage of allowing sampling of larger cortical regions for their evoked responses. This allowed larger spaces between adjacent electrode penetrations, so that somatotopic organization would become more readily apparent. Also, since cerebral cortex contains up to six distinct cellular layers, response of a single cell in a given cortical layer may not be representative of the overall activity in a given cortical column. Unit-cluster recording has a disadvantage, as compared to single-unit recording, in not allowing precise quantitation of evoked activity to a given stimulus used to evoke the response. The sphere of cortical activity recorded utilzing unit-cluster methodology is related to the size of the exposed microelectrode tip. The single-unit recorded in unit-cluster methodology is the evoked response of a single cell, or group of cells responding nearly simultaneously, to a perburbing stimulus.

Raccoons were pre-treated one hour prior to general anesthesia with 1mg acetyl promazine and 0.02mg/lb atropine administered intramuscularly (IM). Immobility and traquilization were induced with 10mg/lb ketamine and 2mg/lb xylazine IM, endotracheal entubation was performed. General anesthesia was induced and maintained by either 2-3% methoxyflurane in 95% oxygen administered via a gaseous anesthetic machine or by intraperitoneal injection of diallyl-barbituric acid (144mg/kg) and urethane (463mg/kg) given as needed.

The skin over the sagittal midline of the skull was incised, the temporalis muscles retracted by periosteal incision and elevation to expose the skull surface. A 75mm hole was bored into the parietal bone overlying S-I and enlarged with ronguers to identify the area of interest about the medial and lateral central sulci. The muscles of the limbs contralateral to the S-I exposure, were dissected via a craniolateral approach on the proximal limb leading into a lateral approach on the distal limb. The individual muscles were dissected along intervening fascial planes, identified and kept moist with K-Y jelly. By tapping an exposed muscle belly (or its accompanying tendon) sharply the spindle reflex was elicited shortening the muscle belly, relaxing the antagonistic muscles and causing subsequent movement at the appropriate joint(s). This was utilized during the experiment to identify the muscle (by its action), test the integrity of muscle

spindle input centrally after the dissection was completed and to evoke muscle afferent activity in the cerebral cortex during mapping when 100Hz vibration was not being used.

The raccoon's skull was stabilized prior to recording by use of wood screws implanted in the frontal sinuses and occipital crest, fastened to brass rods with dental acrylic which in turn were connected to a stable surface on which the micromanipulator was located. The dura was then removed and mineral oil layered over the exposed cortical surface to prevent its dehydration.

Glass coated tungsten microelectrodes (shaft diameter 20-60μm, 10-20μm uninsulated tip exposed) were utilized to record evoked sensory activity in the cortex. The microelectrode signals were amplified 1000X, filtered at 80Hz (low) and 10 KHz (high) frequencies before display on an oscilloscope and being made audible over an audio monitor. A grid pattern of microelectrode penetrations were spaced 0.5mm apart in the anterior-posterior direction and 1.0mm apart in the mediolateral plane as they pierced the cortical surface of interest perpendicularly. Prior to each electrode penetration the electrode tip was dipped in 30% HRP (Sigma type VI, in 0.05M Tris buffer pH =8.3) to facilitate visualization of the electrode track in subsequent histologic sectioning. An electrical ground was placed in the cervical musculature.

Mechanoreceptive activity was evoked by tapping, stroking or pulling the muscles, tendons or integument with nonconductive materials (e.g. a wooden stick or the rubber gloved hand). Joint afferent activity was evoked by passive flexion, extension or rotation of the joint under examination. 100Hz vibration of less than 0.5mm amplitude was applied directly to muscles in which one end of a silk suture had been placed deeply in to the muscle and the other end tied to an audio speaker driven by a sinusoidal generator. The frequency and amplitude of the vibration applied to the muscle could be varied and individual muscles tested in this manner without interference by evoked cutaneous mechanoreceptive inputs.

To mark cortical areas of interest, an electrolytic lesion was placed in the white matter just below the cortex by passing 10μA of current through the electrode for one second. In this way the cytoarchitecture above the lesion was preserved so that it could be determined.

At the end of a mapping experiment the planes of electrode penetrations were determined by the placement of two marking electrodes. Subjects were overdosed with general anesthetic and perfused in preparation for histological sectioning of the mapped cortical area.

A left lateral thoracotomy was performed, the descending aorta clamped, 5ml of 1% sodium nitrate followed by 500U of heparin were infused into the left

ventricle. The right auricular appendage was severed and the perfusion needle placed into the left ventricle. The perfusion sequence consisted of 750ml saline, one liter 2% paraformaldehyde/2% glutaraldehyde in 0.1M phosphate buffer, 750ml of 3% sucrose in phosphate buffer. Perfusion was performed under pressure sequentially as specified. The brain was removed and the mapped cortical area blocked in the plane of electrode penetrations by the method of Johnson (et al., 1974). The cortical block was placed in 10%, 20% and 30% sucrose - phosphate buffer solutions on the next three succeeding days. The embedded block was frozen on the microtome stage in 30% sucrose (a cryo-protectant) at the temperature of dry-ice and serially sectioned at 60 m. The sections were reacted for HRP by the cobalt intensification method of Adams (1977) to visualize the electrode tracks, and then counterstained to visualize Nissl substance with thionine.

Fourteen raccoons were utilized in the experiments. Topological mapping was performed on all fourteen subjects. Evoked muscle afferent cortical activity were further characterized by varying the type of stimulus capable of evoking activity in cortex. Stable units (either single-units or unit-clusters) of reliable repeatability of evoked kinesthetic activity were examined for convergence (response to stimuli of differing submodalities) of muscle and cutaneous information, and for response to 100Hz stimulation.

Figurine maps were constructed in the manner of Rose and Mountcastle (1952) from the data accumulated in each mapping experiment. These display a plane of electrode tracks on an appropriate tissue section drawing, with the effective receptive field displayed at each point along the electrode track where unit activity was recorded. In this way a histological location was correlated with a particular physiologically mapped receptive field. The final data was displayed as general muscle representation areas on a drawing of the unfolded cortical surface as visualized by the author.

The boundaries of the muscle afferent projection zone in anterior S-I of the raccoon were then delineated in Nissl stained histologic sections of the mapped cortical area. This allowed microscopic evaluation of the cytoarchitecture for each cortical area mapped. The results were compared to those previously discussed in the monkey, cat and raccoon (Jones and Porter, 1980; Johnson, et al., 1982).

SECTION 5: RESULTS

All experiments involved extracellular microelectrode mapping in the left cerebral cortex with stimulation of the contralateral body surface. Fourteen raccoons were utilized in these mapping experiments. Eight animals (Table 5-1) were used in preliminary exploratory studies of the sulci surrounding primary somatic sensory cortex using a 1mm × 1mm grid pattern of electrode penetrations. The electrode was advanced dorsoventrally 200μm between attempts to evoked cerebral cortical units. In these preliminary studies 209 electrode penetrations yielded 157 responding loci of which 37 were responsive to mechanical stimulation of contralateral muscles, the remaining responding to cutaneous stimulation.

In the remaining six animals, the central sulci and their deep banks were mapped in detail by a finer grid of electrode penetrations (1mm spacings mediolaterally, 0.5mm spacings anteroposteriorly and 200μm dorsoventrally between recording sites). In all but one animal (84528) the electrode was advanced to form each row of penetrations in the anterior-posterior direction, with subsequent histological sectioning in the

Table 5-1

Summary of 1 mm Grid Exploratory Experiments

Animal Number	No. of Penetrations	Area Explored	Findings
82558	27	MC & LC sulci	Distal antebrachial muscle responses on the anterior banks of the medial LC and lateral MC sulci
83501	19	lateral arm of MC sulcus	Distal antebrachial muscle responses on the anterior bank and fundus of the lateral MC sulcus
83502	13	LC sulcus	No muscle responses, heterogeneous zone responses on the posterior bank of LC sulcus
83504	20	medial arm of MC sulcus	Proximal hindlimb muscle responses on the posterior bank and fundus of MC sulcus, adjacent to the IB sulcus
83505	15	medial arm of MC sulcus	Distal hindlimb muscle responses on the posterior bank, fundus and deep anterior bank of MC sulcus near its medial tip
83506	37	LC sulcus and bridge area	Multiple digit and phalangeal joint responses on the bridge and posterior bank of LC sulcus. Distal antebrachial muscle responses on the medial anterior bank of the LC sulcus
83507	40	medial arm MC sulcus	Small hindlimb muscle response area on the posterior bank of the MC sulcus
83510	22	lateral arm of MC sulcus	Distal antebrachial muscle responses on the anterior bank of MC sulcus, lateral to a proximal antebrachial muscle response area, near the IB sulcus

para-sagittal plane. In 84528 the electrode was advanced to form mediolateral penetant rows with histological sectioning in the frontal plane. In these six raccoons 280 electrode penetrations yielded 521 responding loci of which 118 were evoked by mechanical manipulation of the contra-lateral denuded muscles.

Section 5.1: Classification of 100Hz Evoked Muscle Responses in Kinesthetic Cortex

Although 100Hz vibration is selective for primary muscle spindle response which exhibit frequency locking capabilities (M.C. Brown, *et al.*, 1967), recording of cerebral cortical responses to this type of peripheral stimulation revealed a higher level of central processing of the incoming afferent information (discussed further in section 6.3).

Five types of cortical responses were elicited by 100Hz vibratory stimuli in the 85 muscle afferent loci tested. These were categorized as follows: 1) no response; 2) rapidly adapting units evoked only at the onset of 100Hz stimulus (ra onset); 3) rapidly adapting units evoked only at the termination of 100Hz stimulation (ra offset); 4) rapidly adapting units which responded at both the onset and termination of 100Hz stimulation (ra on/off); 5) slowly adapting units which responded as long as stimulus was applied, and whose frequency of firing appeared to have a phase relationship to the

frequency of vibratory stimulus applied to the muscle belly when varied from 30-300Hz (SAαHz).

Table 5-2 is a summary of the data from the six fine grid recording experiments. From this table it is apparent that the majority of 100Hz responsive loci were of the rapidly adapting type (an average of 68%) (usually of the ra onset type, 50%) the rest were slowly adapting (32%). The type of rapidly adapting response seemed to be idiosyncratic to the individual animal under investigation.

Section 5.2: Figurine Maps

The figurine maps of the six fine grip mapping experiments are presented sequentially in this section. In Figures 5.2-5.7, the presentation of data for each of the fine grid experiments begins with a gross drawing of the cerebral cortical surface of the raccoon showing the location of the rows of electrode penetrations for that cortical map. The gross topological view of the cortical map is followed by a series of figurine maps for that experiment. Figure 5-1 presents a model figurine chart which demonstrates the method of information coding contained in each figurine (explained in the figure legend). For each row of electrode penetrations, the figurine map is broken into two components, a response chart depicted above a drawing of the appropriate histological section. Photographs of histologic sections

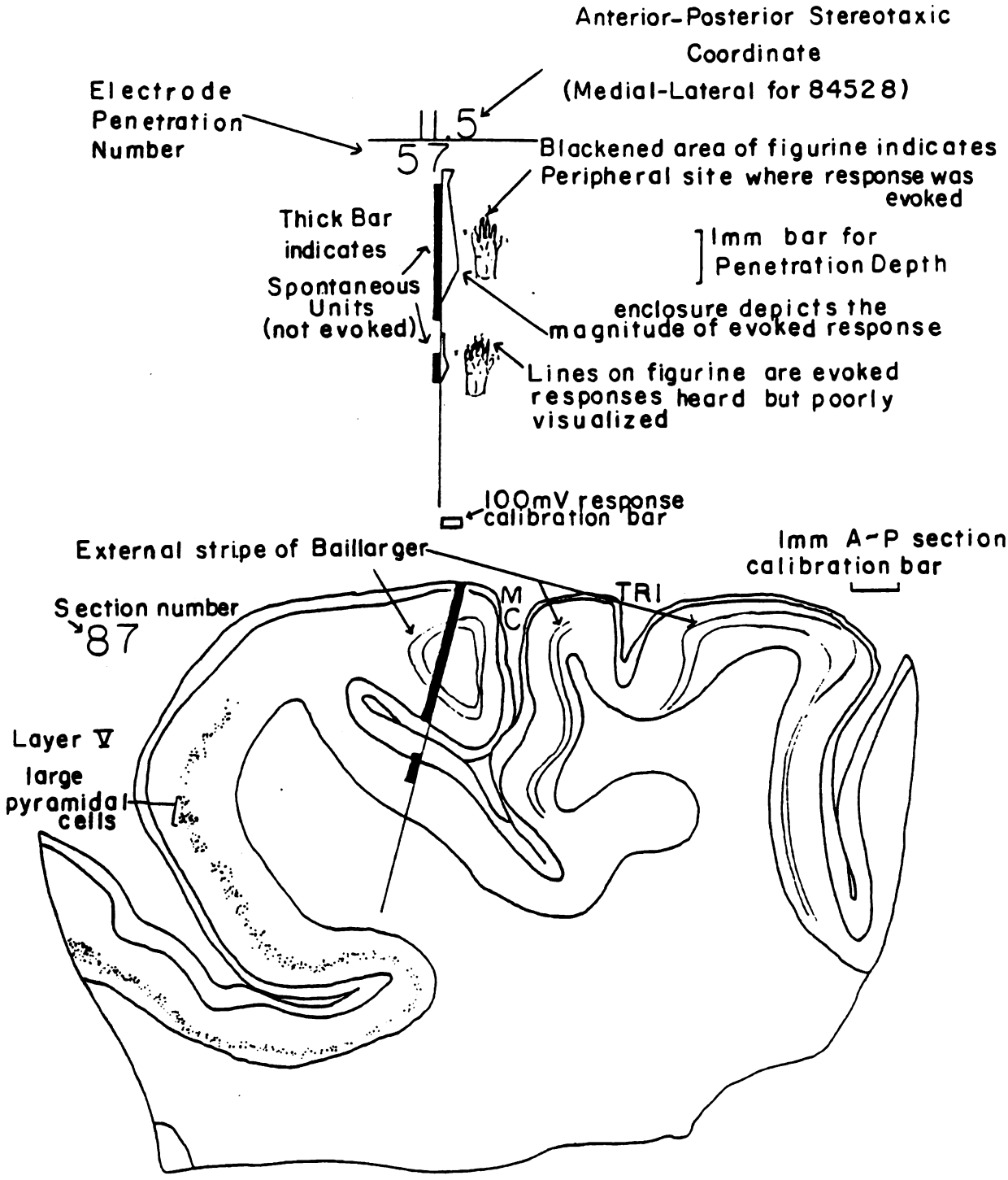
TABLE 5-2

SUMMARY OF DATA FROM SIX FINE-MAPPING EXPERIMENTS

Animal number	84513	84514	84515	84518	84521	84528
Area Sampled	lateral LC	lateral MC	medial MC	MC	TRI/MC lateral	MC/LC lateral
Penetrations	17	52	28	61	64	58
Responding loci	20	121	57	98	110	115
<u>Muscle loci</u>						
total	7	25	17	27	20	22
100Hz tested	0	18	0	25	20	22
100Hz responsive	-	12	-	19	12	14
ra onset	-	8	-	4	4	12
ra offset	-	0	-	10	0	0
ra on/off	-	2	-	0	0	0
SA Hz	-	2	-	5	8	2
% 100Hz stimulated	-	67	-	76	60	63
% RA	-	83	-	74	33	86
% SA	-	17	-	26	67	14
<u>RA muscle responses</u>						
% onset	-	66	-	22	33	86
% offset	-	0	-	52	0	0
% on/off	-	17	-	0	0	0

Figure 5-1:

Six figurine maps presented sequentially in this section depict evoked response charts encoded with information as displayed in the opposite model figurine. Each line in the figurine depicts a single electrode penetration. The heavy bar to the left of the penetration line indicates cortical areas where spontaneous unit activity was recorded, associated with the electrode tip being in the cortical gray matter. The lined open areas to the right of each penetrant line has a width proportional to the amplitude of the units evoked (35-300 V) by mechanical manipulation of the body. Adjacent to the right of the evoked response areas is a figurine drawing of the peripheral receptive field (area blackened) capable of evoking the response. Figurine areas with lines drawn through them depict receptive fields capable of evoking audible responses only (no oscilloscope response). The following abbreviations are used in the drawings: ra = rapidly adapting; sa = slowly adapting; sw = slow wave response; D = dorsal; V = ventral; L = lateral; S = muscle response not driven by 100Hz stimulation; S = muscle response driven by 100Hz; mm = muscle; arrows = motion about a joint; C = claw; sa Hz = frequency locking muscle response (see Section 5.1); MC = medial central sulcus; LC = lateral central sulcus; IB = interbrachial sulcus; TRI = triradiate sulcus. All calibration bars in the drawings are equal to 1mm. Above each figurine map along a horizontal line are the anterior-posterior coordinates (medial-lateral in 84528) of the row of penetrations. Above each penetrant line is the penetration number in that experiment.


Anterior-Posterior Stereotaxic Coordinate
(Medial-Lateral for 84528)
Electrode Penetration Number
11.5
57
Blackened area of figurine indicates Peripheral site where response was evoked
Thick Bar indicates
Spontaneous Units (not evoked)
1mm bar for Penetration Depth
enclosure depicts the magnitude of evoked response
Lines on figurine are evoked responses heard but poorly visualized
100mV response calibration bar
External stripe of Baillarger
1mm A-P section calibration bar
Section number
87
M
C
TRI
Layer V
large pyramidal cells

are included for animals 84518 and 84528 to demonstrate electrode track visualization. In the drawings of histological sections, S-I can be identified by the inclusion of the outer stripe of Baillarger in the drawing. Area 4 is identified in the drawing by the inclusion of the large layer V pyramidal cells (see Figure 5-1.

Figurine maps do not superimpose perfectly onto the histological sections due to variable shrinkage and stretching of the tissue during processing. All histological sections are in the para-sagittal plane except 84528 which is in the frontal plane.

The following is a summary of the location and extent of fine grid mapping in the last six recording experiments:

84513: Two rows of penetrations explored the lateral extent of the lateral central sulcus (LC).

84514: Six rows of penetrations explored the entire extent of the lateral arm of the medial central sulcus (MC).

84515: Four rows of penetrations explored the medial extent of the LC and the gyral bridge which intervenes between the LC and MC sulci.

84518: Eight rows of penetrations mapped the entire MC and the anterior half of the interbrachial sulcus (IB).

84521: Seven rows of penetrations mapped the entire triradiate sulcus (TRI). In this raccoon the TRI and MC were very closely subjacent.

84528: Twelve rows of penetrations explored the entire MC sulcus and the medial part of the LC sulcus, which in this animal were continuous.

Spontaneous units were recorded on each insertion of the microelectrode when it was located in the cortical gray matter. Spontaneous activity is depicted in the figurine maps, and used to correctly allign the figurine map with the histologic section.

Section 5.3: Results from Raccoon 84513

Seventeen electrode penetrations formed two anterior-posterior rows mapping the lateral portion of the LC sulcus (Figures 5-2, A-C). In the anterior portion of S-I, distal volar digit 3 and its claw are represented on the post-cental gyral crown. Along the posterior bank of the LC sulcus, cortical units were evoked by disjunctive (heterogeneous) receptive fields located on multiple distal digits and claws (Figure 5-2B). Dorsal digit 3 responses were also elicited on the crest of the post-central gyrus along the LC sulcus. No cortical units could be evoked on the lateral portion of the anterior bank of the LC sulcus by stimulation of the contralateral body surface.

Section 5.4: Results from Raccoon 84514

Fifty two electrode penetrations formed six anterior-posterior oriented rows mapping the entire lateral arm

Figure 5-2:

Figurine maps of two rows (oriented anterior-posterior) formed by 17 electrode penetrations mapped the antero-lateral border of the lateral central sulcus in animal 84513. No kinesthetic projections were found in this area. 5-2.A depicts a dorsolateral view of the mapped area in the left cerebral hemisphere. 5-2.B is the more medial of the two rows of penetrations. Along the crest of the post-central gyrus and down the posterior bank of the LC sulcus in this lateral area was the representation of distal volar digit 3 and the digit 3 claw. Weaker subcutaneous whole forearm responses were audible along the posterior bank of the LC culcus. No responses were evoked on the anterior bank of the LC sulcus in this lateral area.

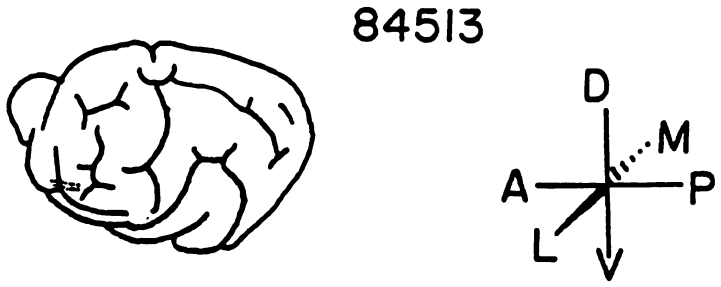
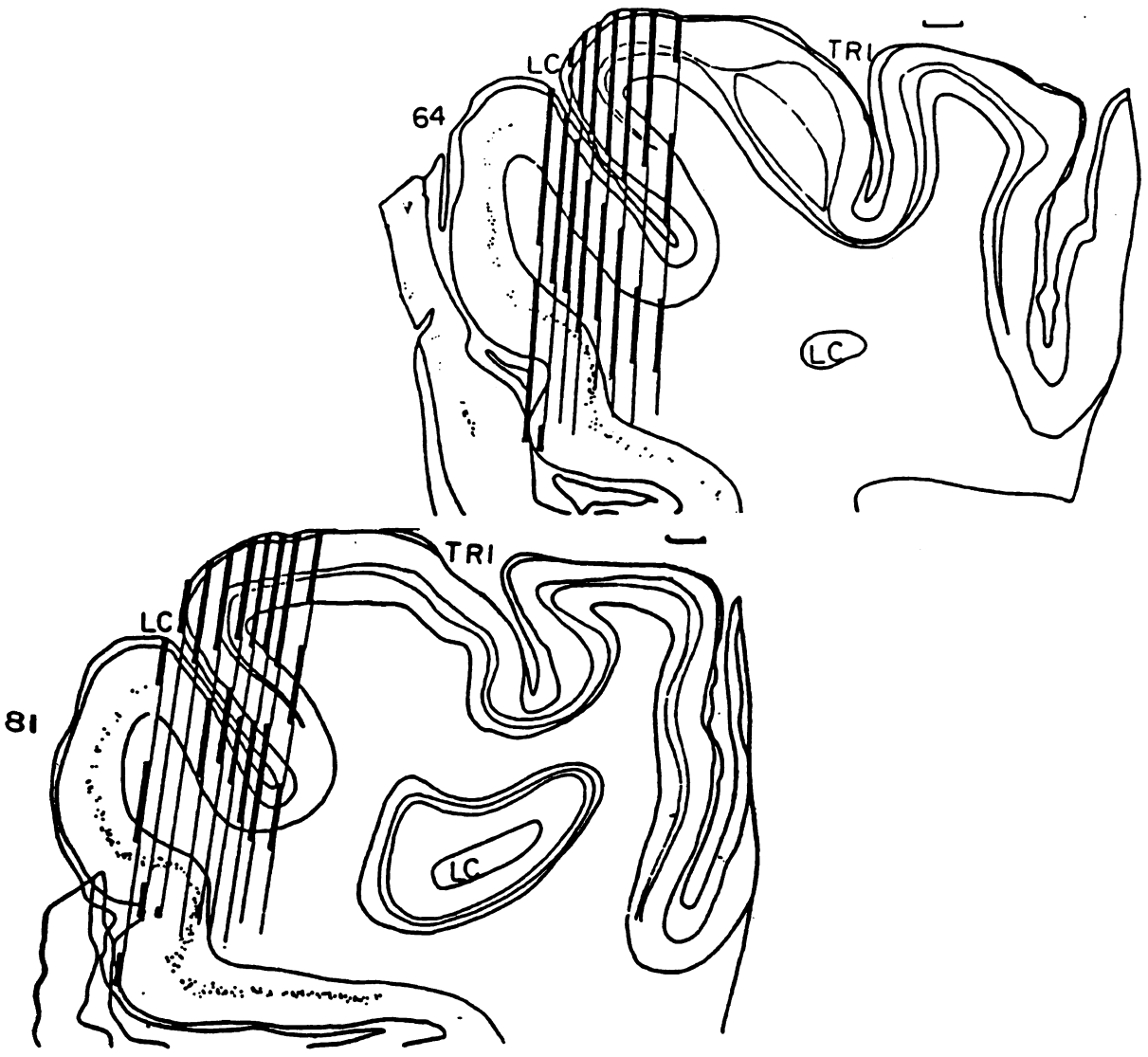


Figure 5-2.A



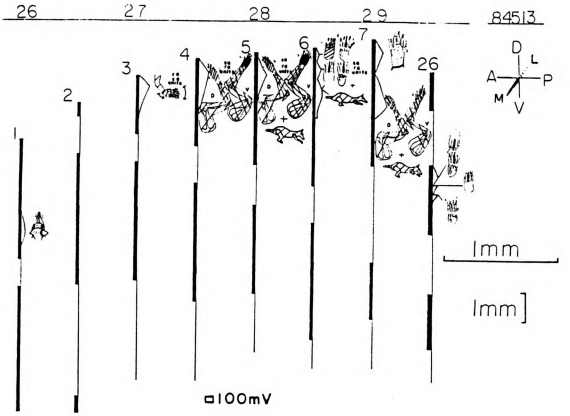
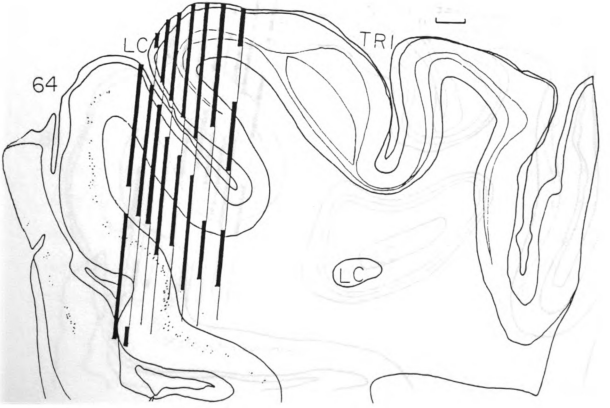


Figure 5-2.B



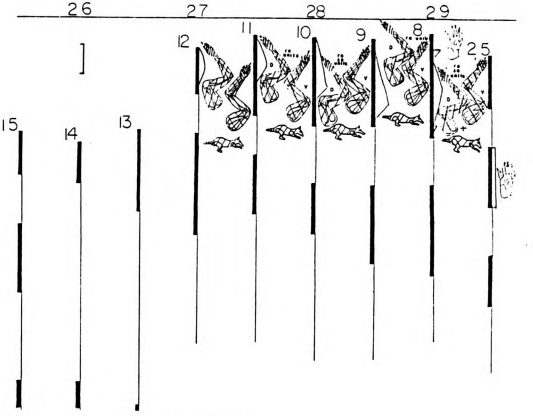
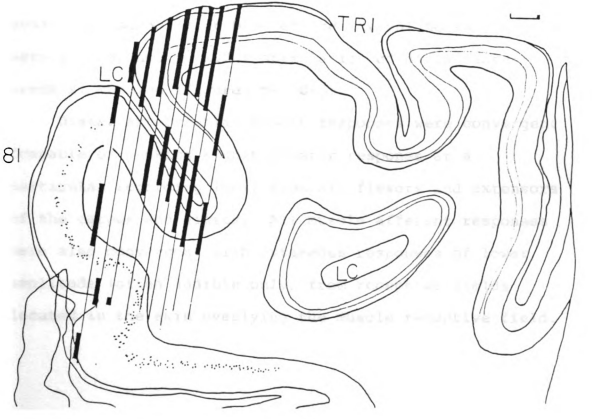


Figure 5-A.C



of the MC sulcus (Figures 5-3.A-G). The gyral bridge, between the MC and LC sulci, was at the anterolateral portion of this mapping experiment. Cortical units were evoked in the gyral bridge and along the posterior bank of the LC sulcus by stimulation of a heterogeneous set of peripheral receptive fields (Figures 5-3.B-E). This heterogeneous set of receptive fields consisted of multiple digit (dorsal and volar) and claw responses, responses from all forearm joints and some muscle afferent responses (not 100Hz stimulated) from muscles distal to the shoulder. In the most lateral portion of the MC sulcus, heterogeneous receptive field responses were also found on both banks of the sulcus (Figures 5-3.C,D) and continuing along the posterior bank further medially (Figure 5-3.E). The remainder of the units evoked on the anterior bank of the lateral MC sulcus were in response to 100Hz stimulation of distal antebrachial muscles (Figures 5-3.E-G).

Distal antebrachial muscle responses were convergent (capable of evoking a unit-cluster response at a particular recording loci) from all flexors and extensors of the carpus and digits. All muscle afferent responses were also convergent with cutaneous responses of lower amplitude (often audible only) from receptive fields located in the skin overlying the muscle receptive field.

Figure 5-3:

Figurine maps of six rows (oriented anterior-posterior) formed by 52 electrode penetrations in raccoon 84514 are depicted serially, from lateral (5-3.B) to medial (5-3.G). Figure 5-3.A above depicts a dorsolateral gross view of the left cortical surface mapped, the entire extent of the lateral arm of the MC sulcus. 5-3.A below is a composite drawing of the histological sections at the level of each row of electrode penetrations. Laterally in the tip of the MC sulcus cortical responses were evoked by a heterogeneous set of digital receptive fields (5-3.A,B,C). Caudally on the post-central gyrus was the representation area of distal volar digit 4 and its claw. Further medially the anterior bank of the MC sulcus was an area where cortical responses were evoked by 100Hz vibration of distal antebrachial muscles (503.E,F,G). On the posterior banks of the MC sulcus were responses to dorsal digit 4 and hand.

Figure 5-3.A

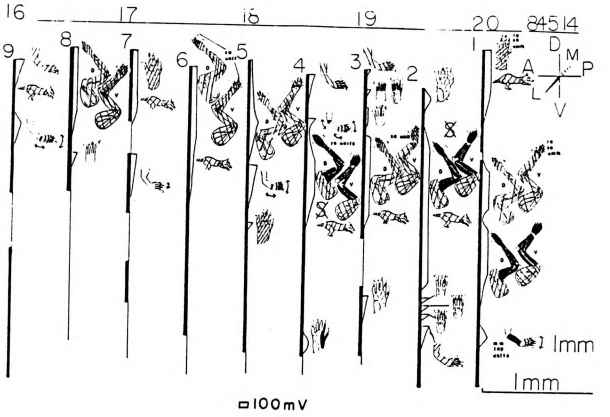
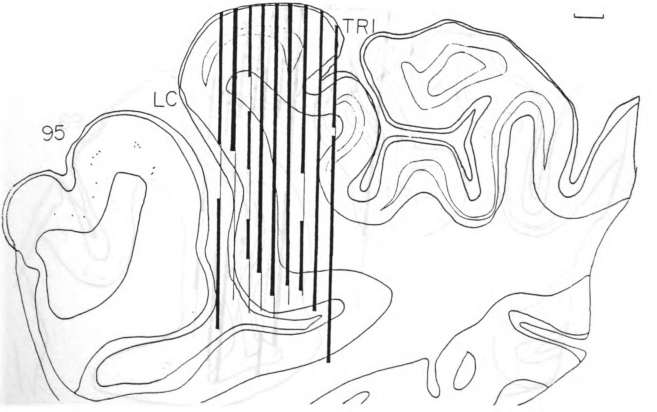


Figure 5-3.B



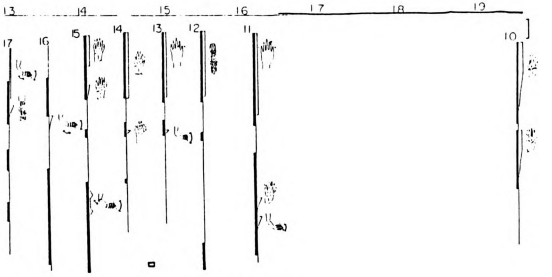
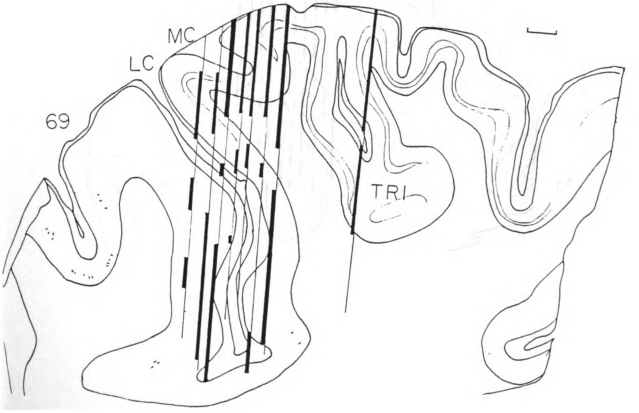


Figure 5-3.C



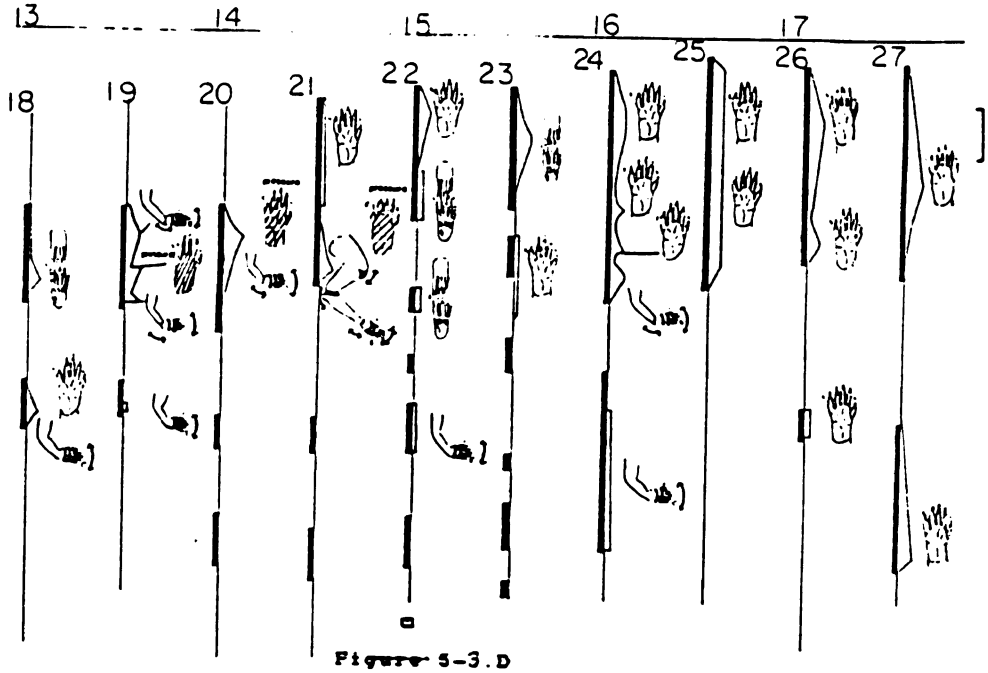
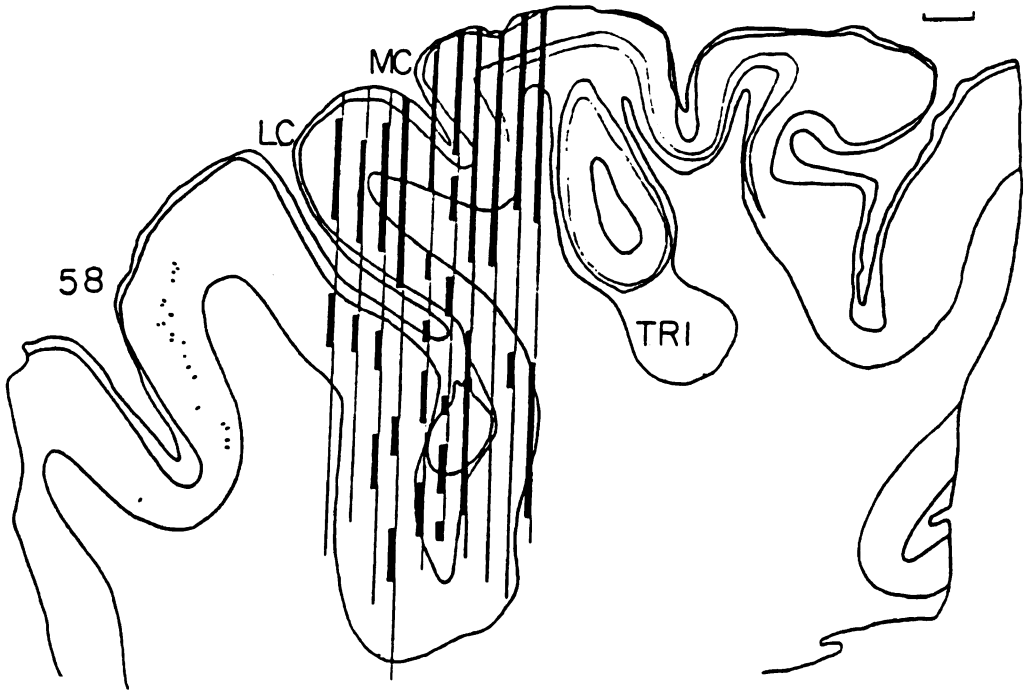


Figure 5-3.D



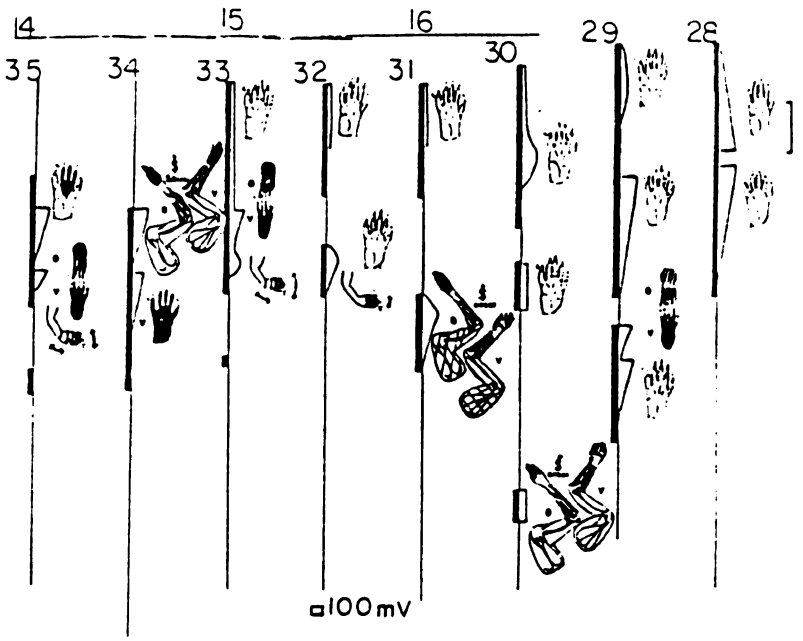
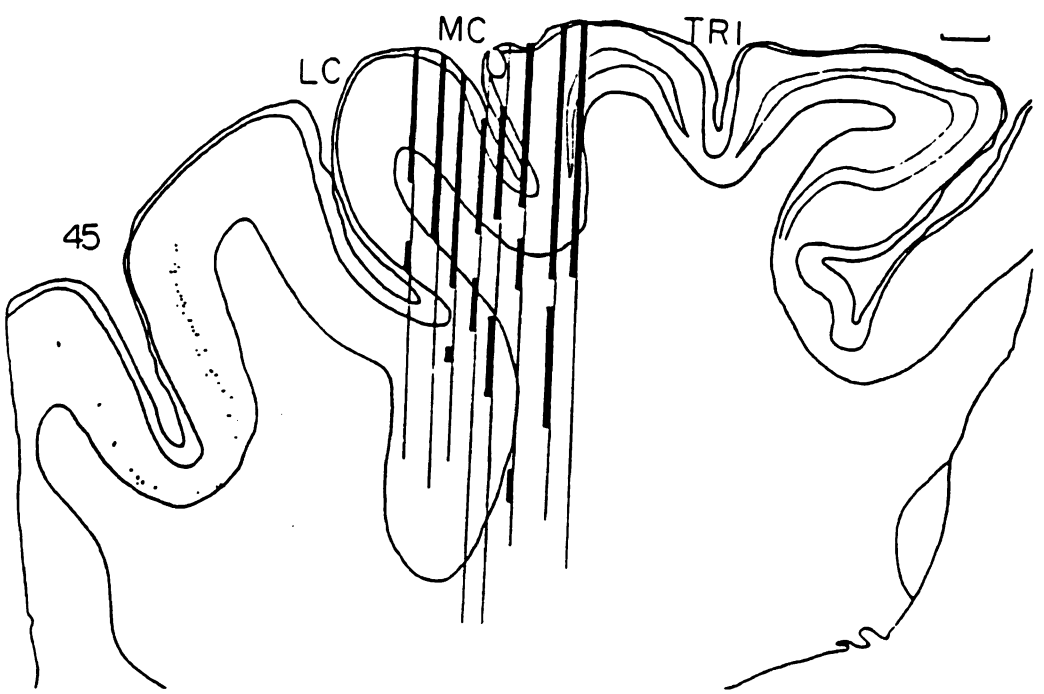
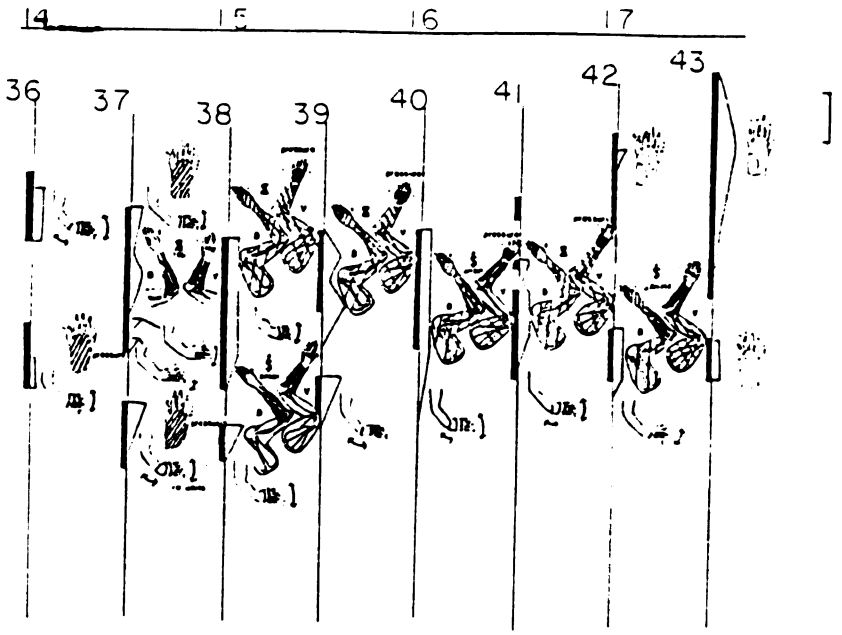


Figure 5-3.E





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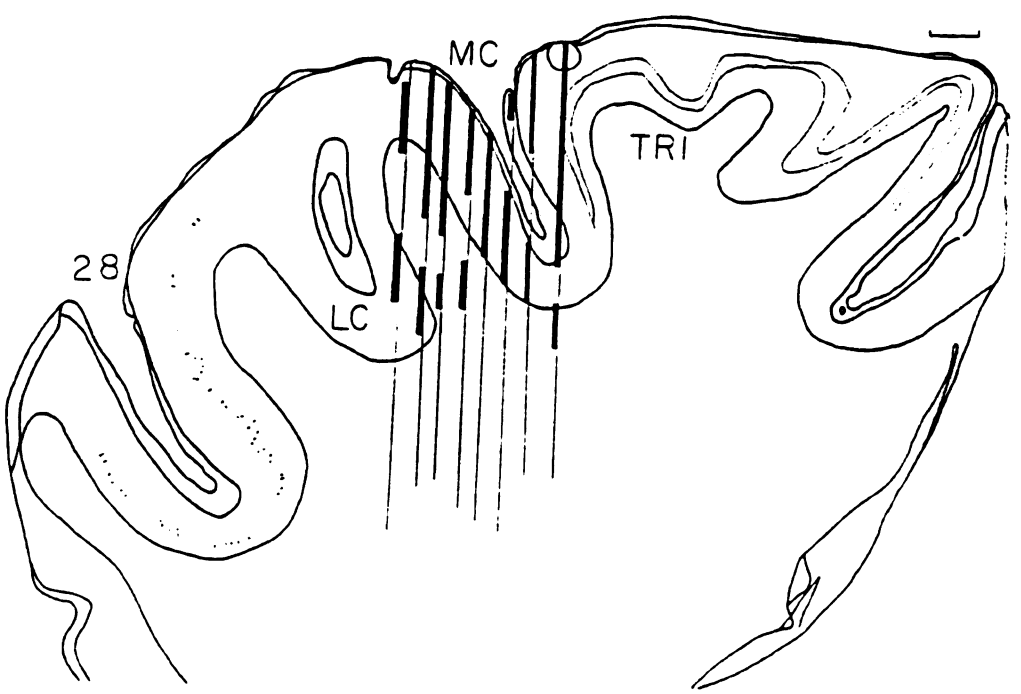


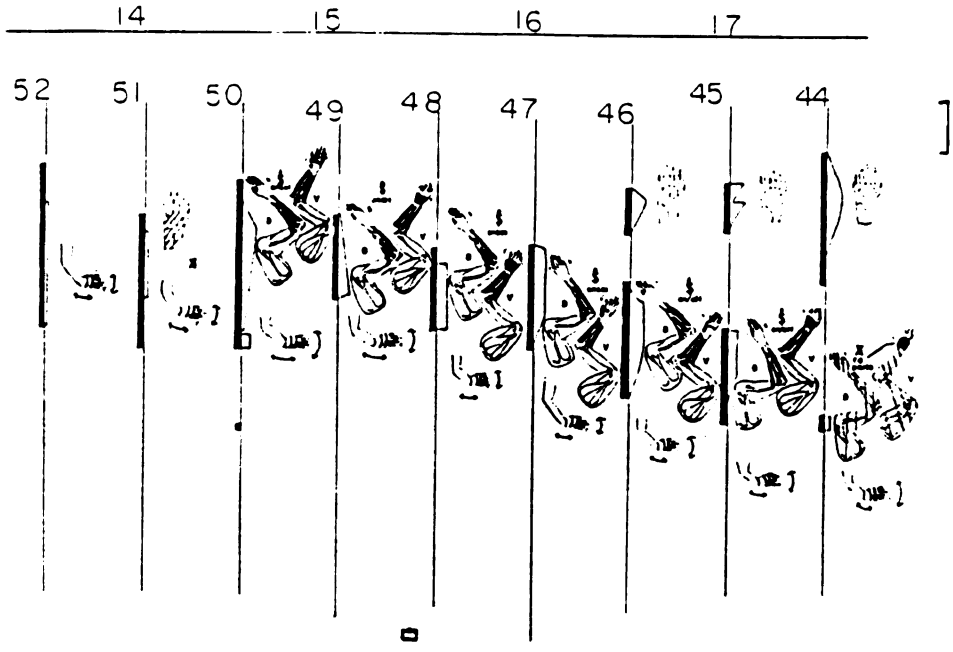
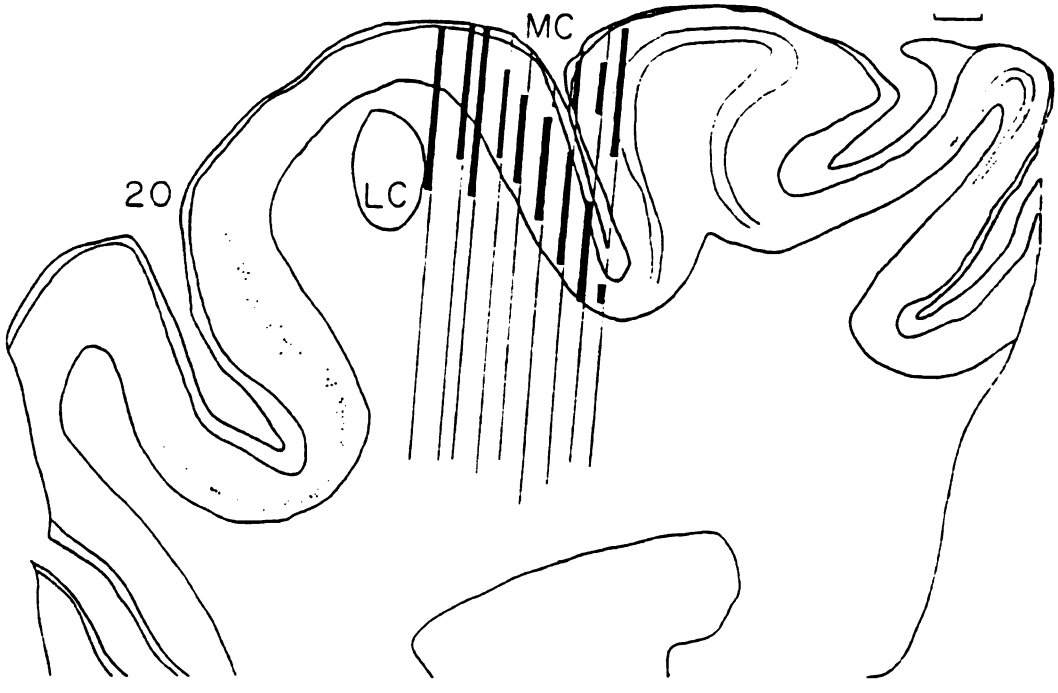


Figure 5-3.G



The post-central gyral crown in this area of S-I receives afferent projections from distal volar digit 4 and the digit 4 claw.

Section 5.5: Results from Raccoon 84515

Twenty eight electrode penetrations forming four anterior-posterior rows mapped the medial extent of the LC sulcus and the gyral bridge area (Figures 5-4.A-E). Multiple digit, claw and volar hand (heterogeneous) receptive fields evoked cortical activity on both the anterior and posterior banks of this medial tip of the LC sulcus and in the gyral bridge area (Figures 5-4.B-E). Metacarpo-phalangeal and phalangeal joint responses were evoked on the anterior bank of the LC sulcus as well (Figures 5-4.B-E). Some distal antebrachial muscle responses (not 100Hz tested) were recorded on the medial portion of the anterior bank of the LC sulcus (Figure 5-4.C). These muscle responses were convergent for all flexors and extensors of the carpus and digits, and also convergent with cutaneous receptive fields which overlie the muscle receptive fields. The post-central gyrus in this area of S-I represents distal digit 3 laterally and distal digit 4 medially.

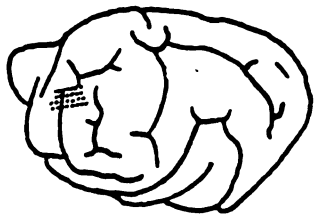
Section 5.6: Results from Raccoon 84518

Sixty one electrode penetrations forming eight anterior-posterior oriented rows mapped the entire MC

Figure 5-4:

Figurine maps of four rows (oriented anterior-posterior) formed by 28 electrode penetrations mapped the medial portion of the LC sulcus in raccoon 84515. 5-4.A above depicts a dorsolateral view of the mapped area in the left cerebral hemisphere, below are serial drawings of histologic sections at the level of each row of electrode penetrations. 5-4.B is the lateral most row with 5-4.C-E sequentially more medial. Anterior to the digit 3 claw representation on the post-central gyrus, on the posterior bank of the lateral LC sulcus are cortical responses were evoked by mechanical stimulation of heterogeneous receptive fields on dorsal and volar digits 3 and 4 and their claws. The anterior bank of this part of the LC sulcus was weakly responsive to passive movement of the contralateral carpal and phalangeal joints (5-4.B,C). A small distal antebrachial muscle responses area was located on the anterior medial bank of the LC sulcus lateral and adjacent to a multiple digit heterogeneous representation area in the medial tip of the LC sulcus.

84515



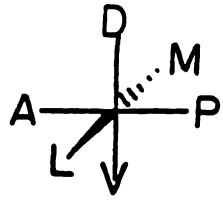
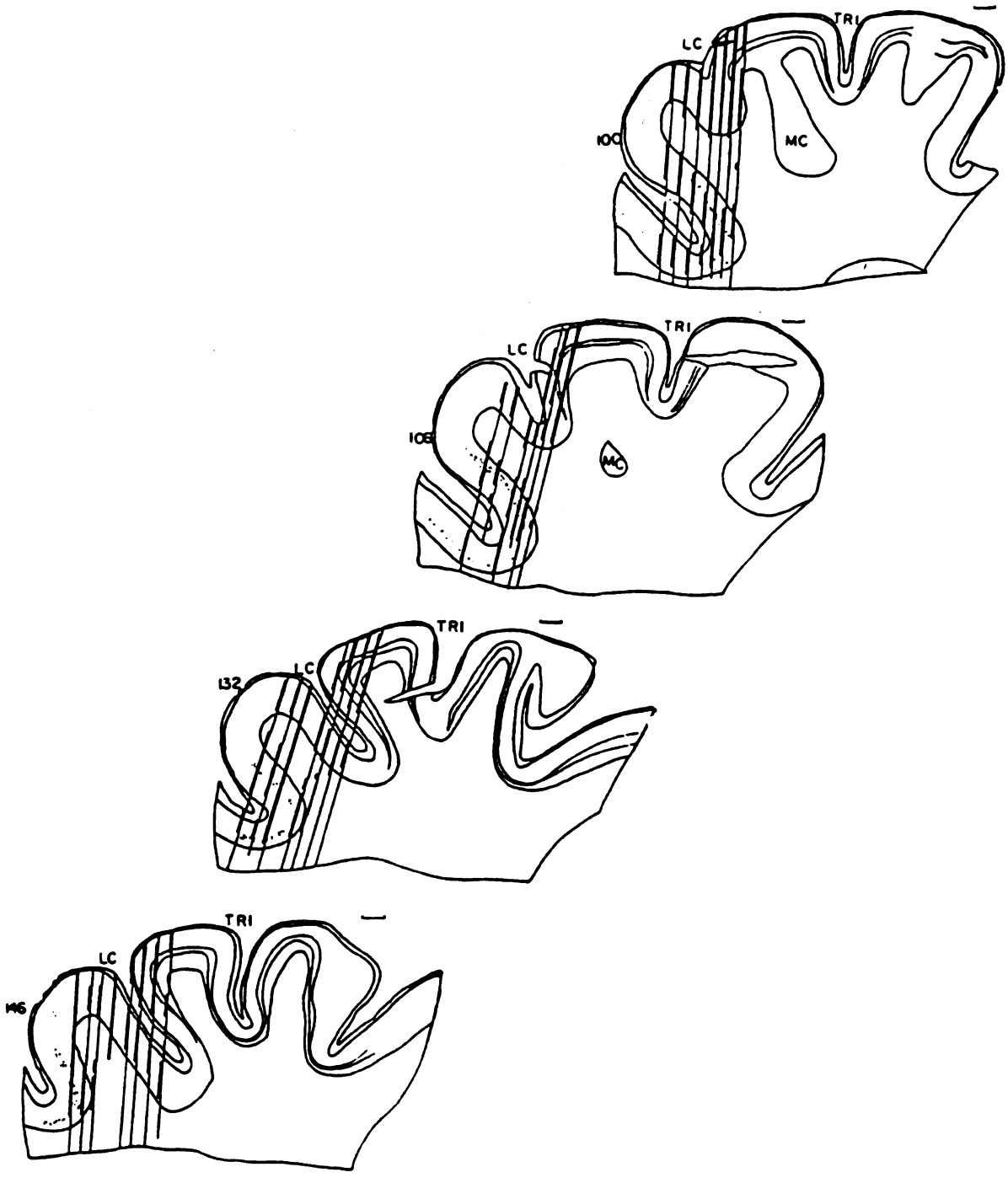
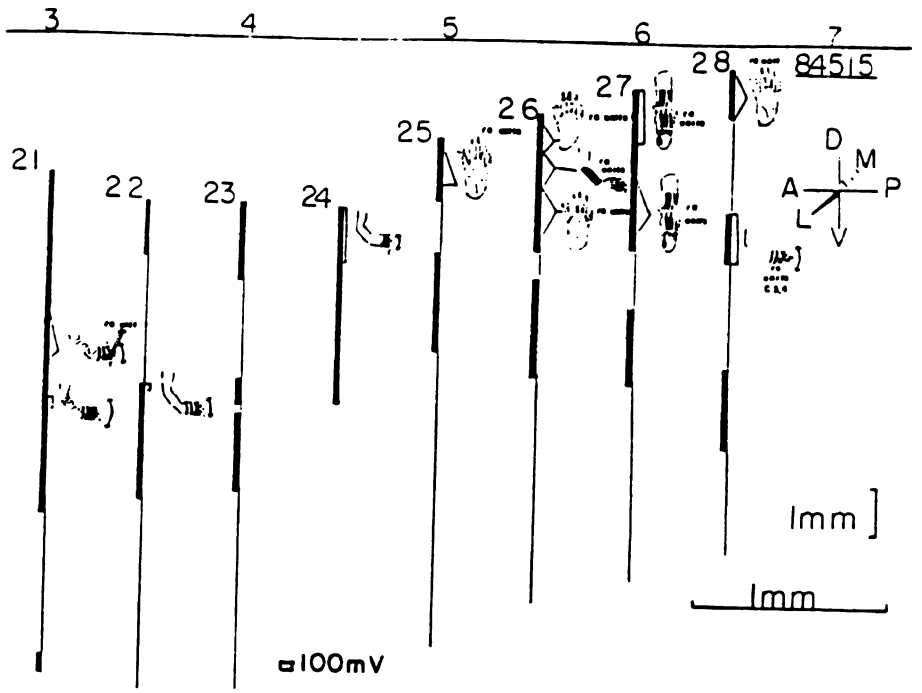


Figure 5-4.A




3
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D
M
A
P
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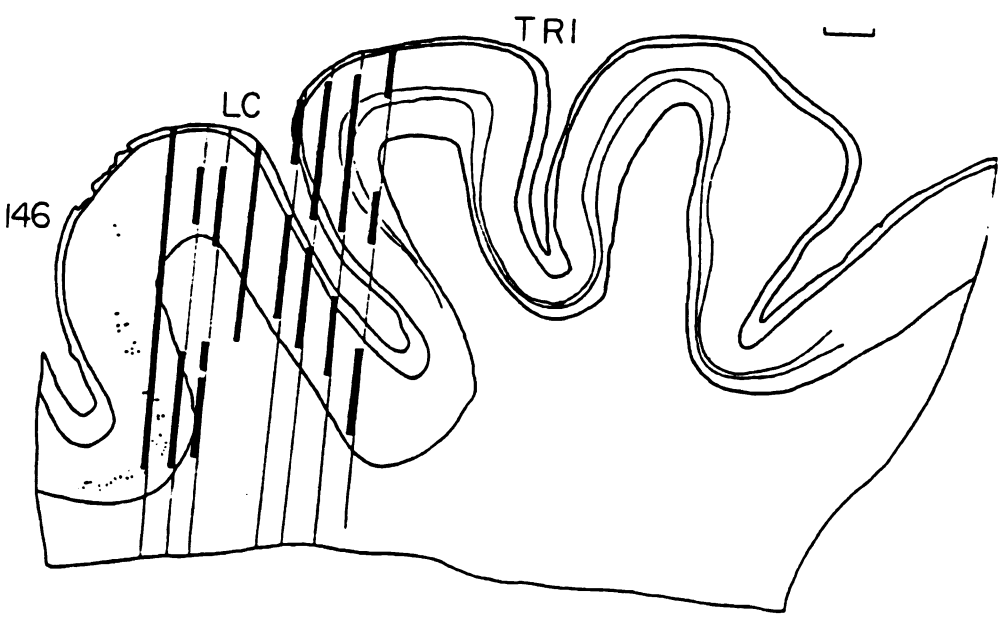
1mm
1mm
100mV

Figure 5-4.B


TRI
LC
146

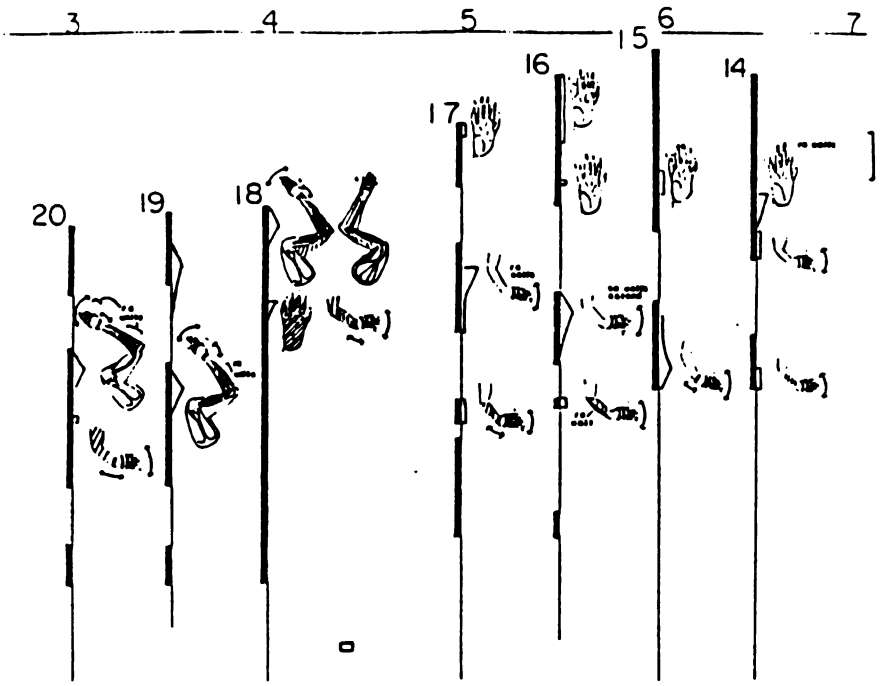


Figure 5-4.C

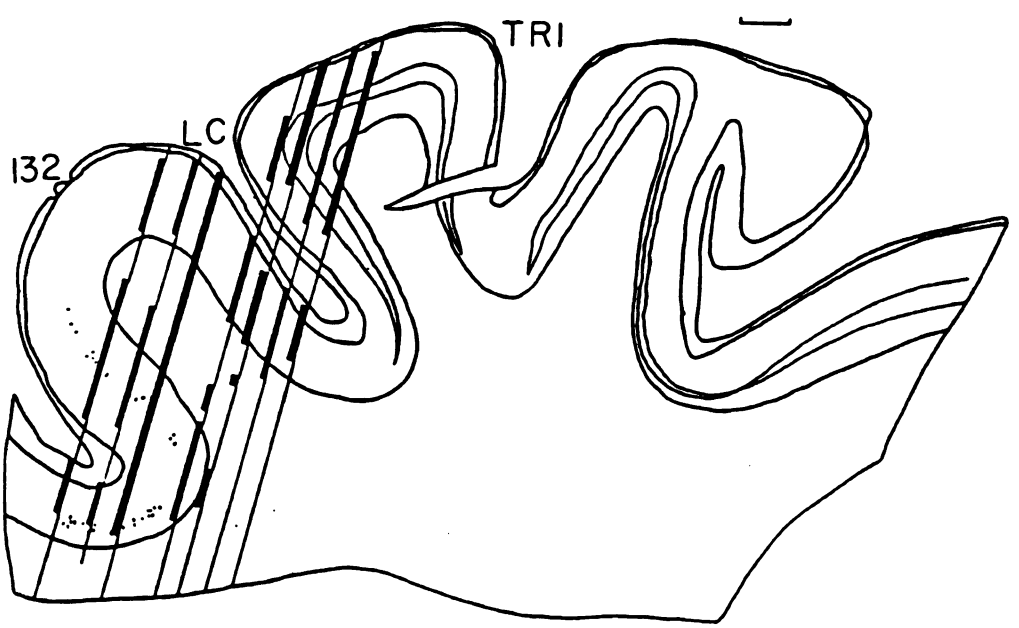
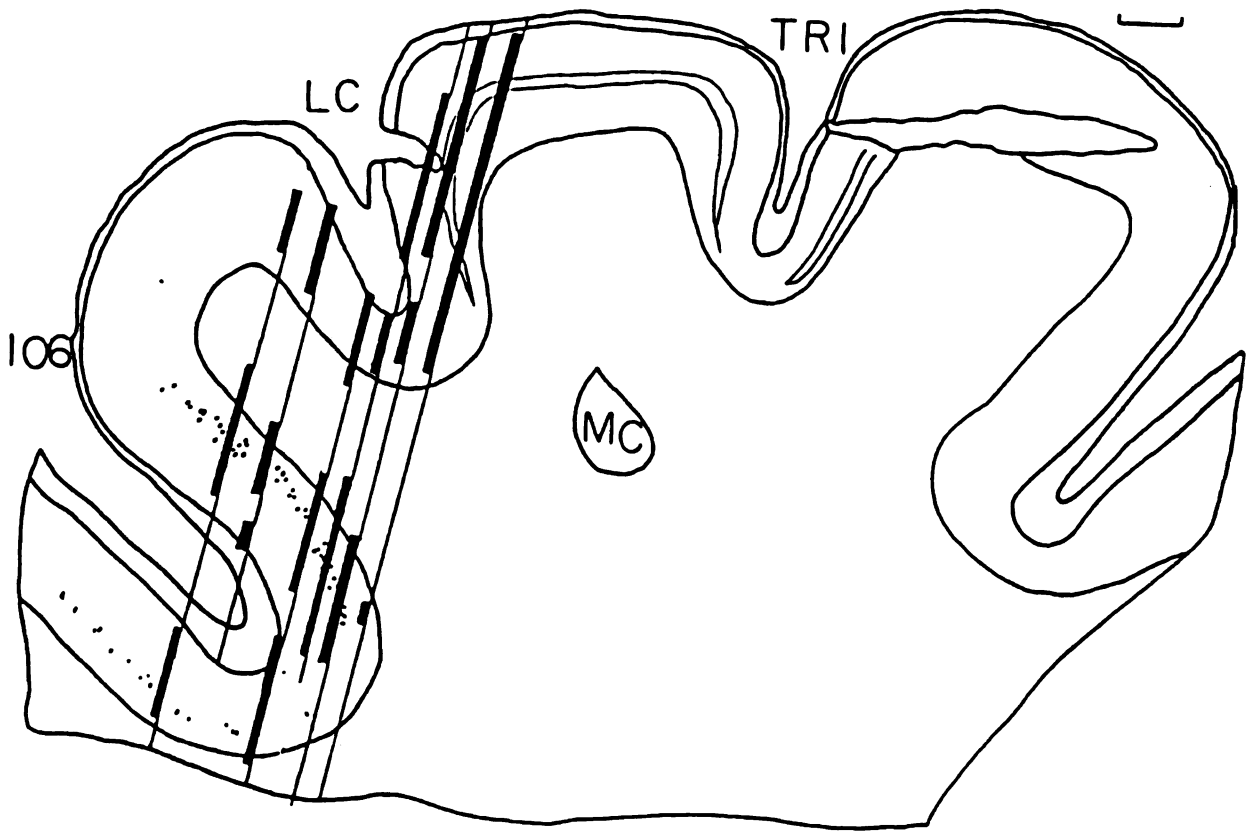


Figure 5-4.D



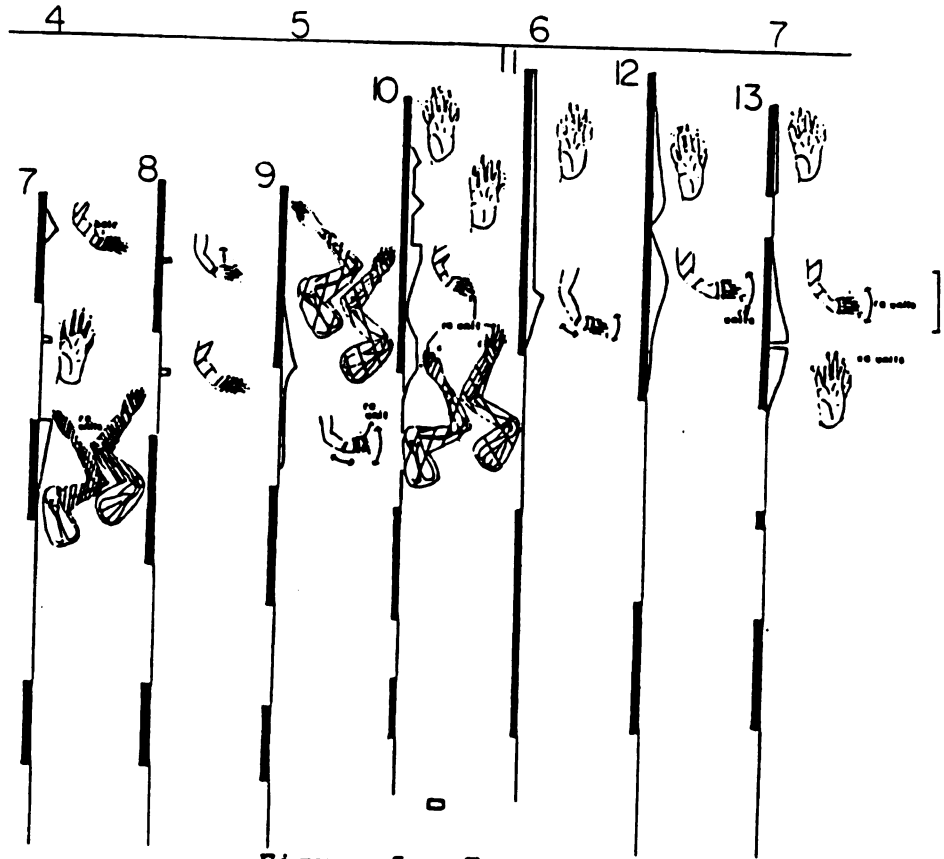
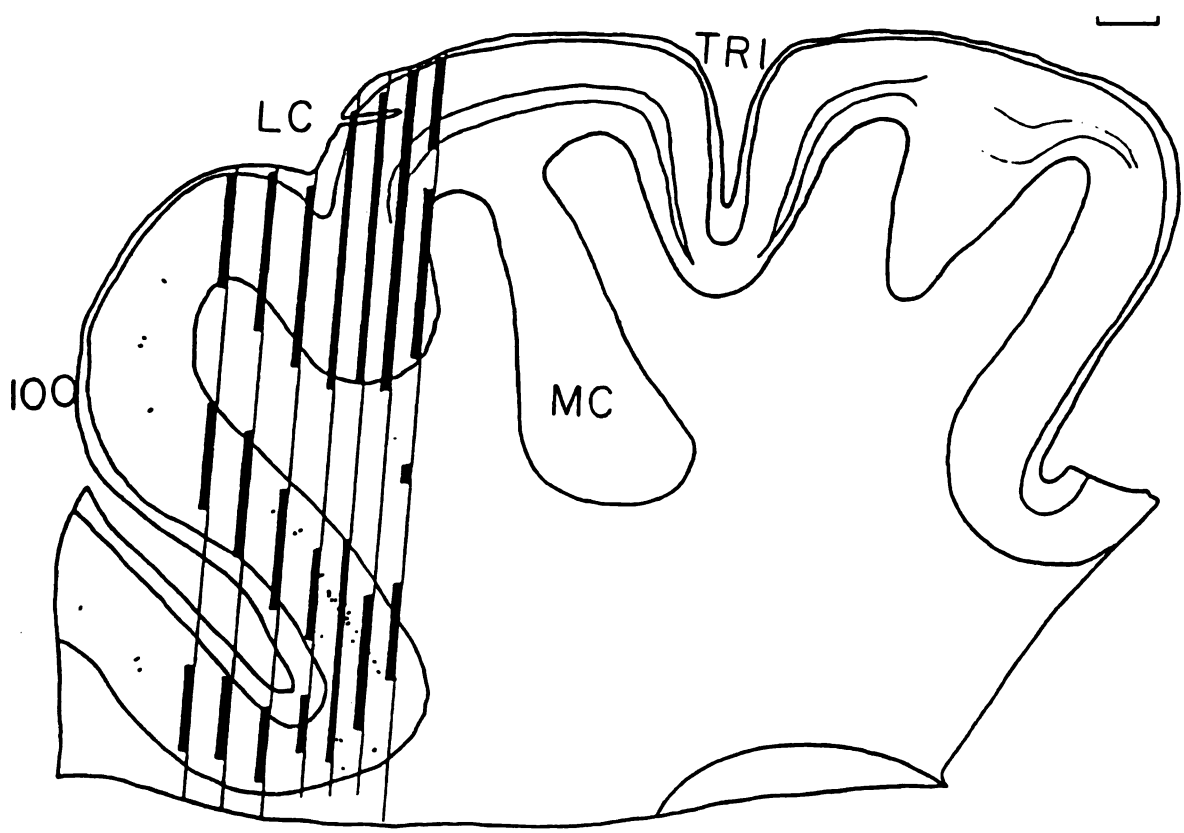


Figure 5-4.E



sulcus in this animal (Figures 5-5.A-I). Cortical units evoked laterally, in the region of the gyral bridge, the posterior bank of the medial LC sulcus and the most lateral tip of the MC sulcus were elicited by stimulation of heterogeneous receptive fields comprised of multiple digit and claws responses (Figures 5-5.B,C). Cortical potentials evoked in the anterior bank of the MC sulcus at the level of the interbrachial (IB) sulcus were in response to 100Hz stimulation of all flexors and extensors of the distal antebrachium (Figures 5-5.D,E). The post-central gyral crown of S-I caudal to the lateral arm of the MC sulcus is a representation area for distal digit 4.

The anterior bank of the MC sulcus just medial to the IB sulcus is a representation area for muscles (not 100Hz responsive) originating on the proximal antebrachium and inserting on the distal antebrachium. Muscles originating on the scapula and inserting on the proximal antebrachium are represented in the fundus region of the MC sulcus medial to the IB sulcus (Figures 5-5.F,G). Scapulo-thoracic muscle representation extends medially along the fundus of the MC sulcus (Figures 5-5.F,G). Flexors and extensors of the shoulder and elbow are convergent in their cortical representation in these areas, and also convergent with low amplitude responses (audible only responses) from overlying cutaneous receptive fields.

Figure 5-5:

Sixty-one electrode penetrations form eight anterior-posterior oriented rows in this mapping of the entire extent of the MC sulcus in raccoon 84518. 5-5.A above depicts a gross view of the mapped area in the left cerebral hemisphere. 5-5.A below are serial drawings of histologic sections at the level of each row of penetrations. 5-5.C-J are the figurine maps of each row, with 5-5.C lateral most the others sequentially more medial. Photographs of the histologic sections from which the drawings are made are on the page opposite the figurine drawing with which they correspond. On the medial posterior bank of the LC sulcus, in the gyral bridge area and in the lateral tip of the MC sulcus, cortical units were evoked in response to stimulation of multiple disjunctive distal digit receptive fields (heterogeneous zone, 5-5.B,C). Medial to the lateral tip of the MC were 100Hz vibration excited distal antebrachial muscle evoked units in the anterior bank and fundus of the MC sulcus (5-5.D) which continued along the lateral edge of the interfundic rise within the IB sulcus (5-5.E). Medial to the IB sulcus on the anterior bank of the MC sulcus were proximal antebrachial and scapular muscle representation areas not responsive to 100Hz stimulation (5-5.F,B). Mechanical stimulation of hindlimb muscles evoked cortical responses in the anterior bank and fundus of the medial (to the IB) portion of the MC sulcus (5-5.H). Multiple hindlimb dorsal and volar digit representation was found on the crest of the post-central gyrus anterior to medial S-I.

84518

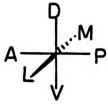
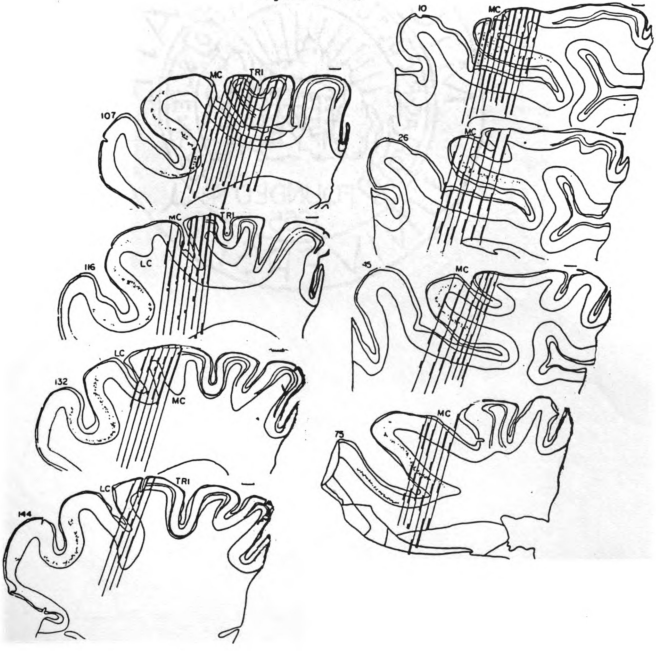


Figure 5-5.A



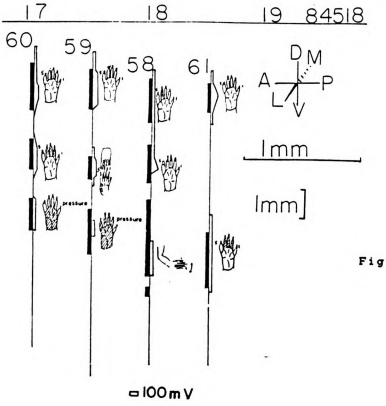
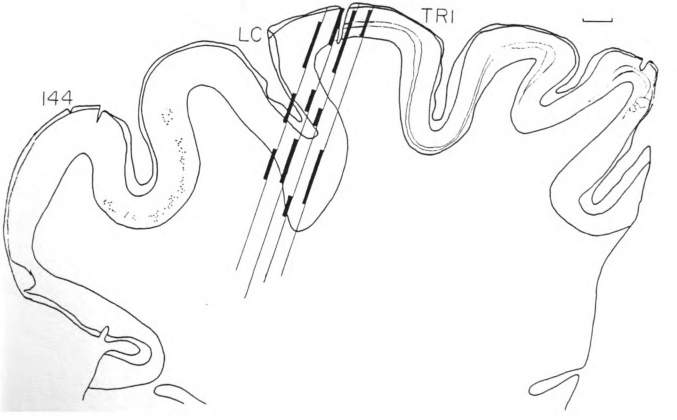
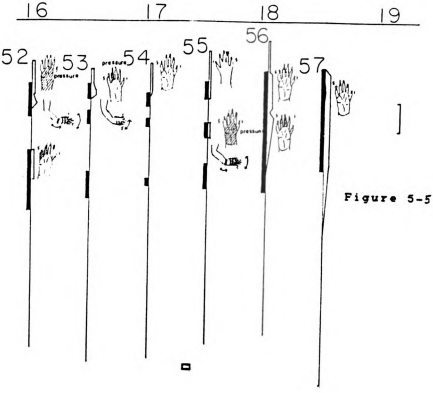


Figure 5-5.B

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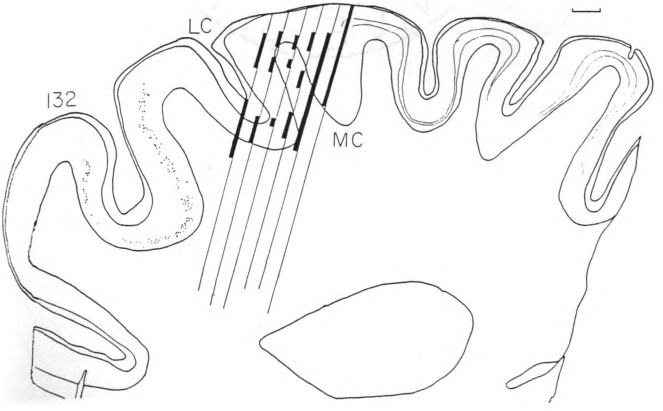
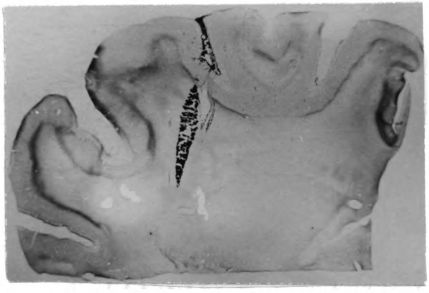
pressure
pressure
pressure

Figure 5-5.c


LC
132
MC



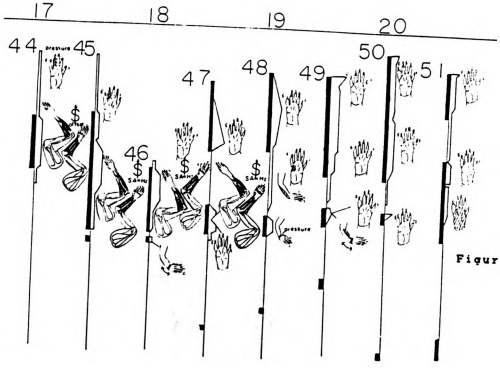
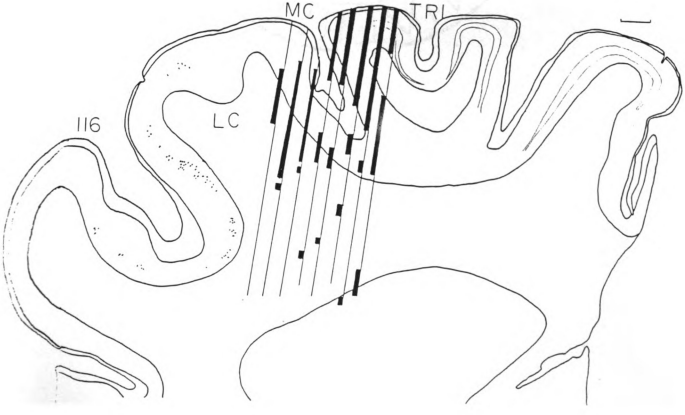


Figure 5-5.D



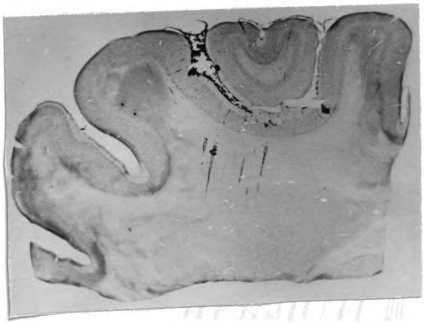
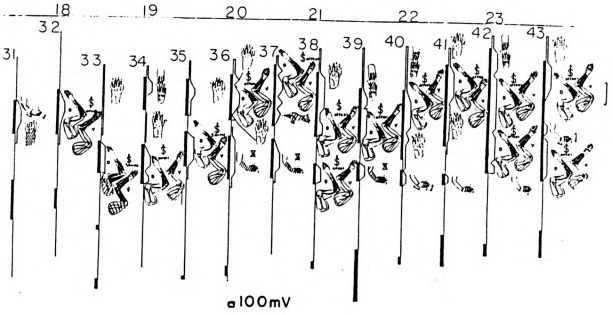


Figure 5-5.E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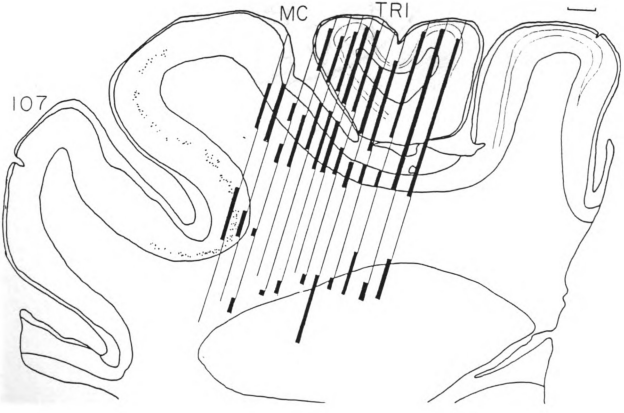
100mV


MC
TRI
107

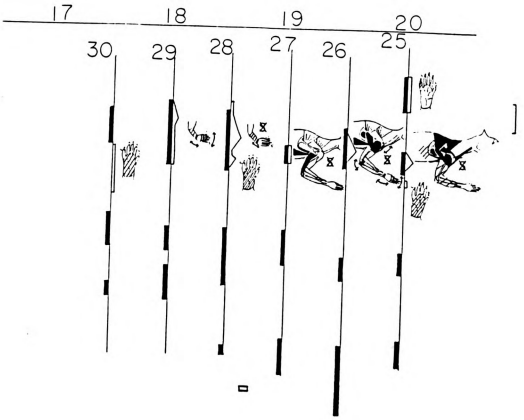
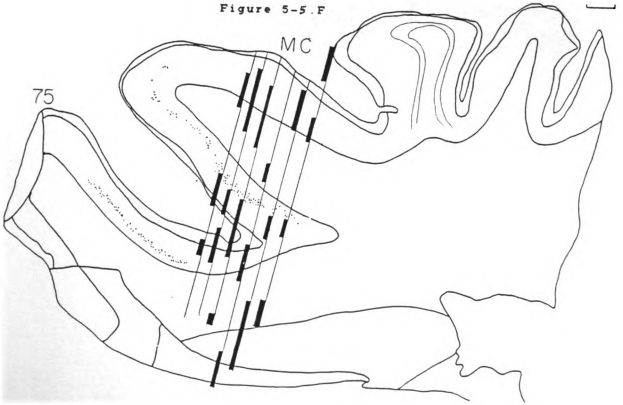
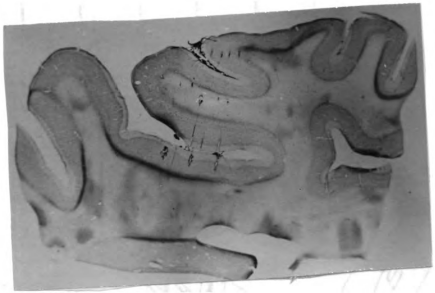


Figure 5-5.F





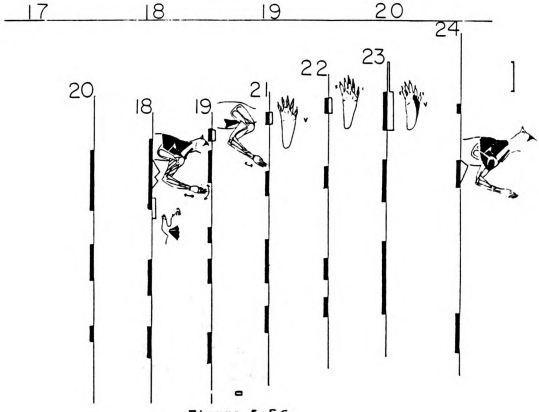
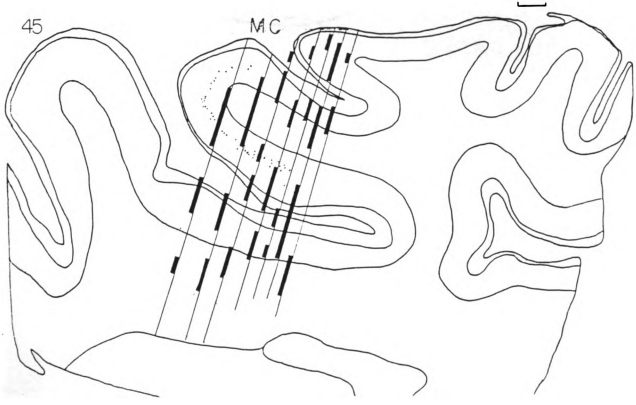
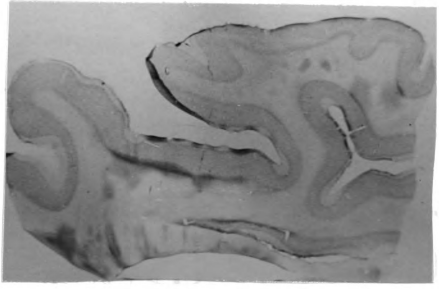


Figure 5-5.G





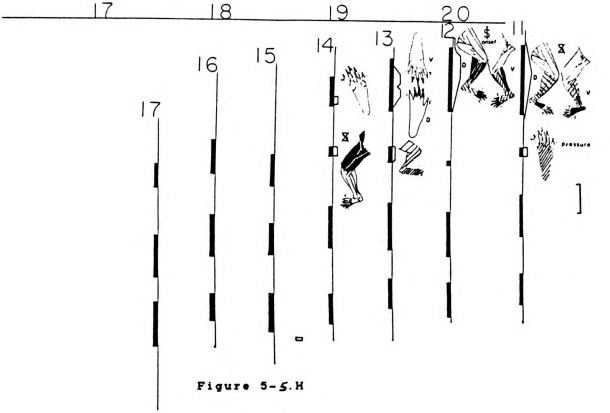
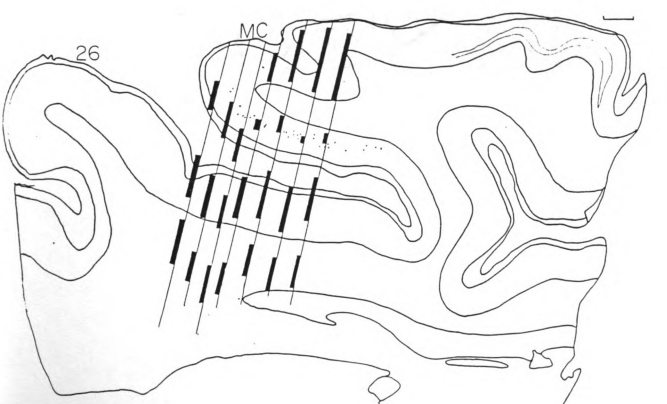


Figure 5-5.H



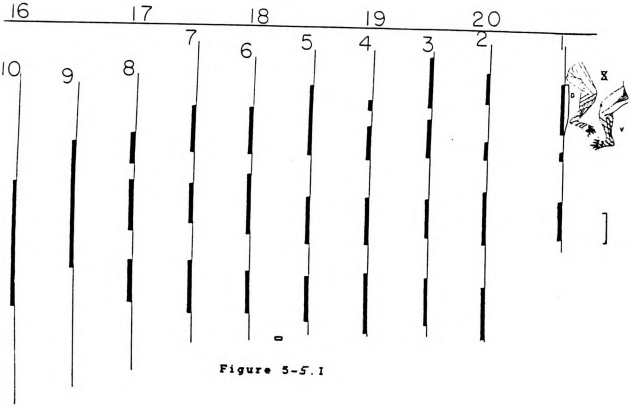
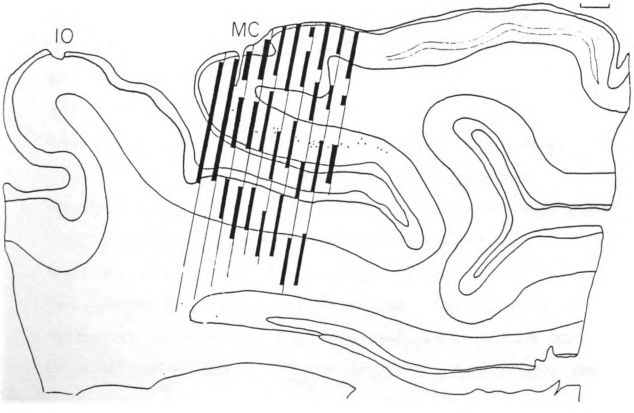


Figure 5-5.1



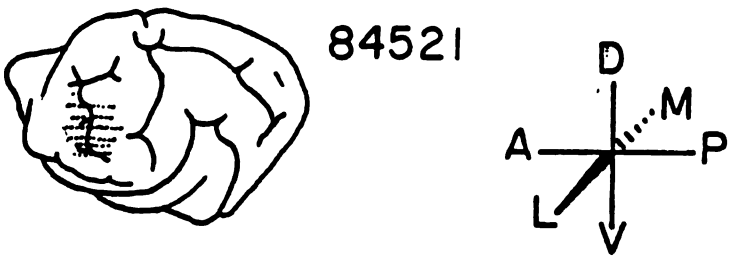
Multiple hindlimb digit and foot (heterogeneous) responses were evoked at the anterior extent of the S-I post-central gyrus area just anterior to hindlimb digit representation (Figures 5-5.G,H). Proximal hindlimb muscles (not 100Hz responsive) were represented on the anterior bank of the most medial portion of the MC sulcus and distal hindlimb muscles in the fundus of this area. Hindlimb muscle afferent responses were convergent for all flexors and extensors about a given joint and also with (audible) responses from overlying cutaneous receptive fields.

Section 5.7: Results from Racoon 84521

Fifty seven electrode penetrations forming seven anterior-posterior oriented rows mapped almost the entire triradiate (TRI) sulcus to a level where it became closely subjacent to the MC sulcus (Figures 5-6.A-H). At the lateral extent of the TRI sulcus, spontaneous unit activity was recorded to an electrode penetration depth of one centimeter into the cortical white matter (Figures 5-6.B,C) unlike any other recording sites encountered in this thesis research. Two 100Hz stimulated distal antebrachial muscle afferent responses were recorded at this lateral TRI margin (Figure 5-6.B) but nowhere else along the TRI sulcus. The majority of responses in the TRI sulcus were from glabrous hand and proximal volar digits (Figures 5-6.B-F). Medial palm was

Figure 5-6:

Fifty-seven electrode penetrations forming seven anterior-posterior oriented rows mapped almost the entire TRI sulcus in raccoon 84521, to a point where it became closely adjacent to the MC sulcus. 5-6.A above depicts a gross view of the area mapped in the left cerebral hemisphere. 5-6.A below are drawings of the histologic sections at each level of the electrode penetrations. 5-6.B-H are the figurine maps of each row with 5-6.B being lateral most, the rest sequentially more medial. The majority of evoked cortical responses in the TRI are from the glabrous palm caudally and proximal volar digits rostrally. Medial palm and radial volar digits are represented laterally in the posterior and anterior banks of the TRI sulcus, respectively (Figures 5-6.B, C,D). Ulnar palm and lateral digits are represented medially on the banks of the TRI sulcus (Figures 5-6.E, F). In this animal the MC and TRI sulci were continuous, grossly. One 100Hz distal antebrachial muscle response was evoked in a deeply buried anterior bank of the MC sulcus (Figures 5-6.G).


84521
D
M
A
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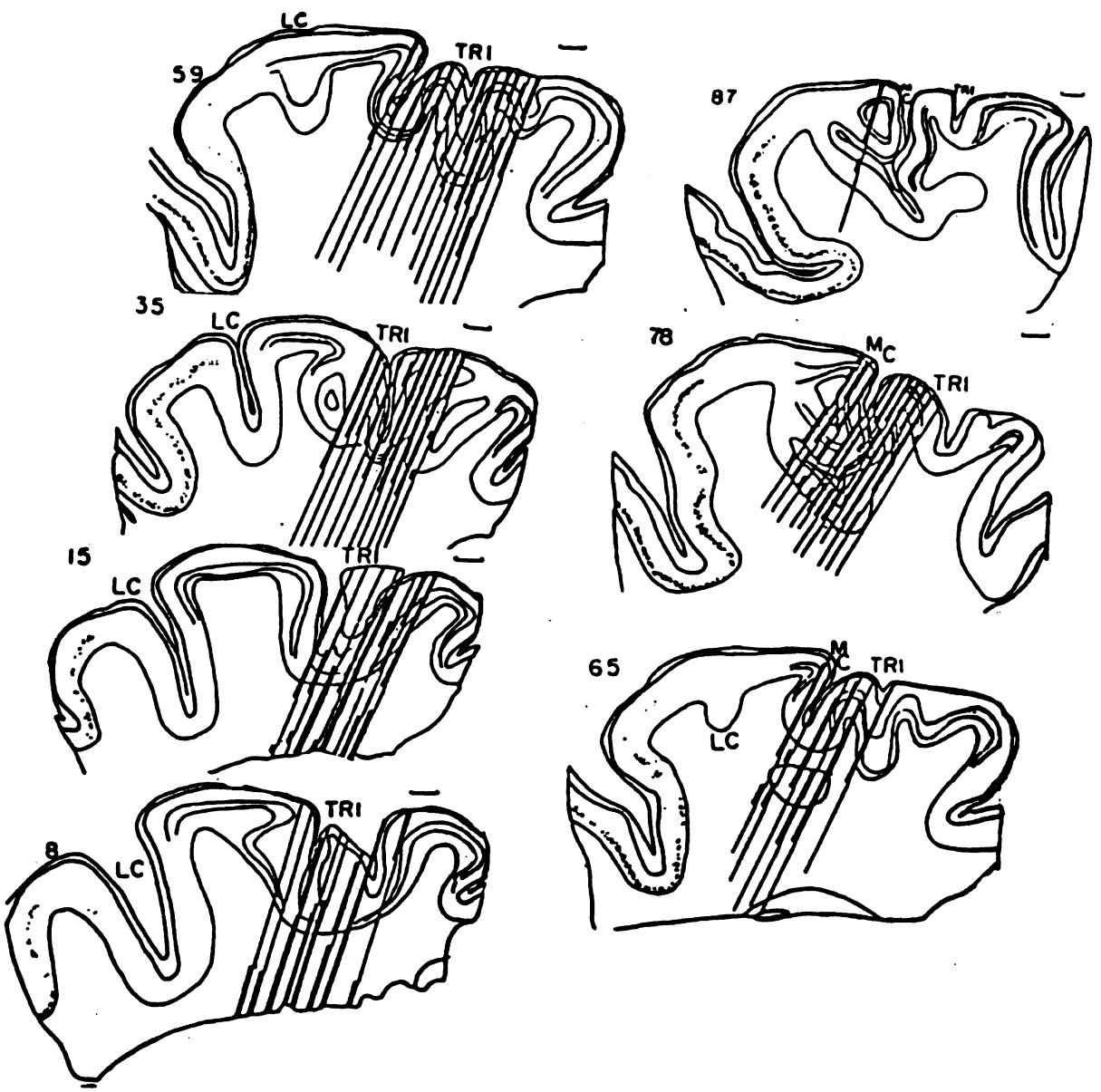
V

Figure 5-6.A


59
LC
TRI
87
35
LC
TRI
78
MC
TRI
15
LC
TRI
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M
C
TRI
LC
8
LC
TRI

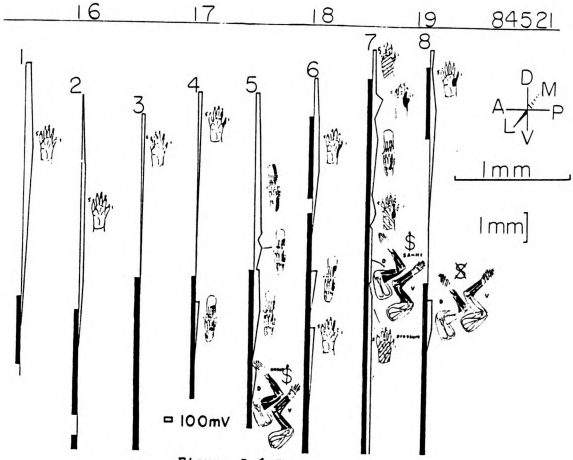
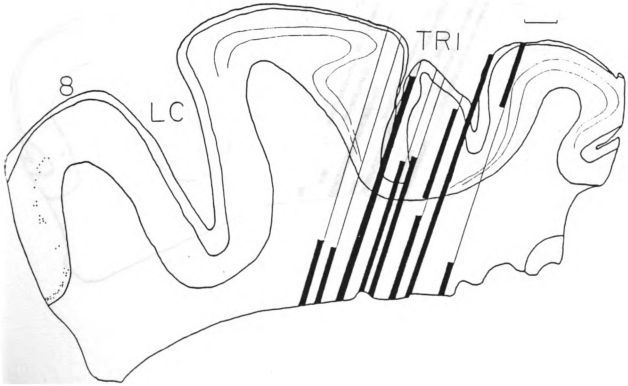


Figure 5-6.B



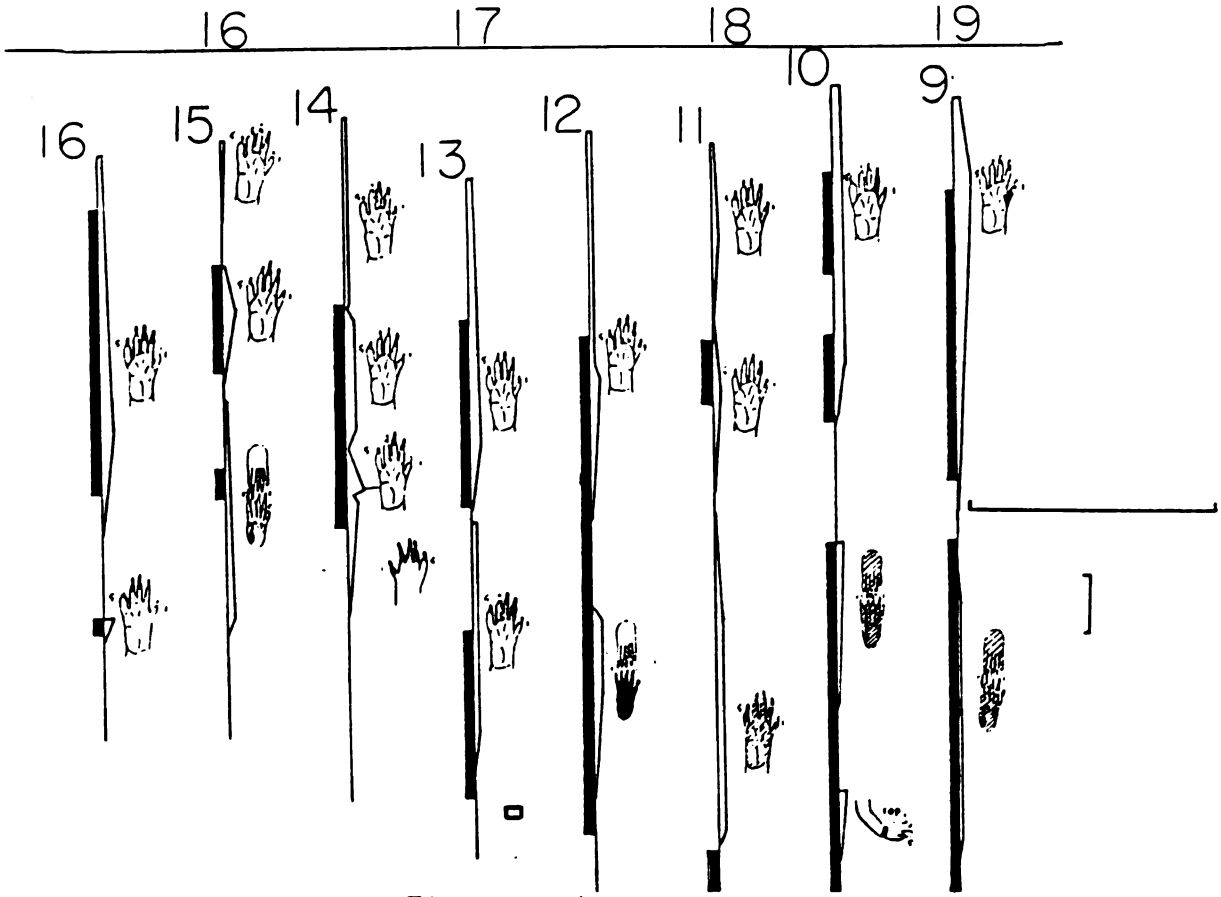
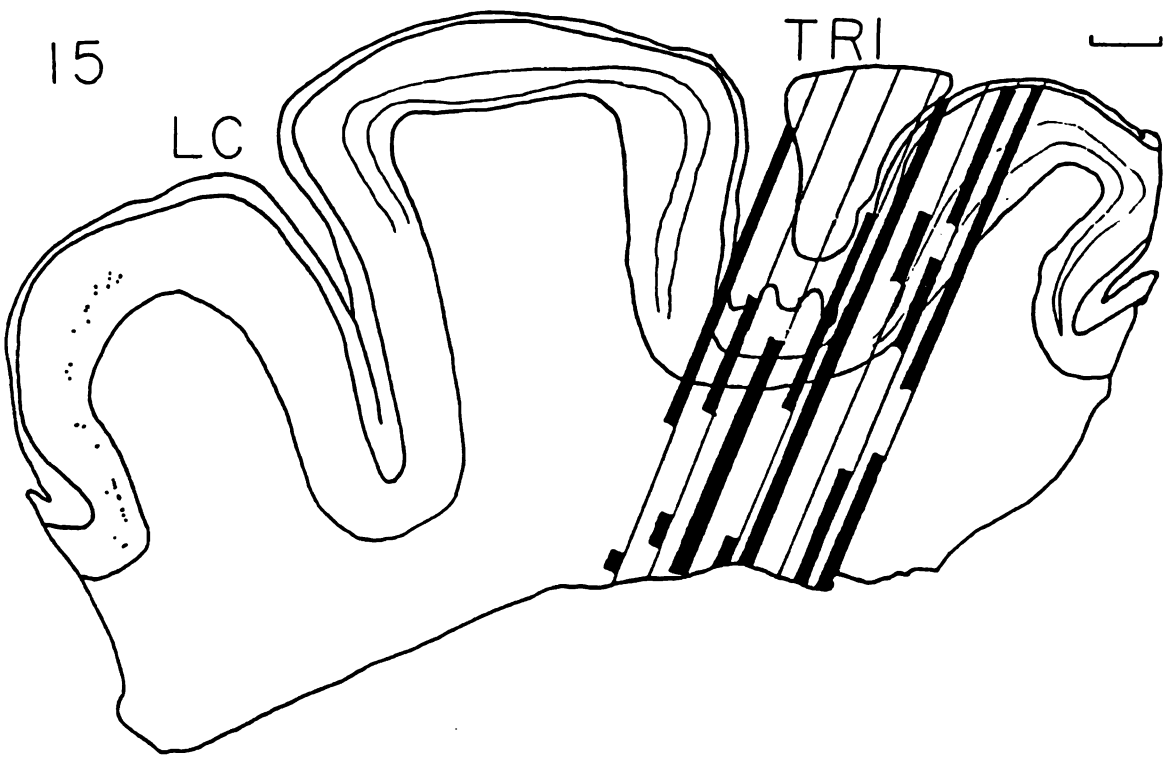


Figure 5-6.C



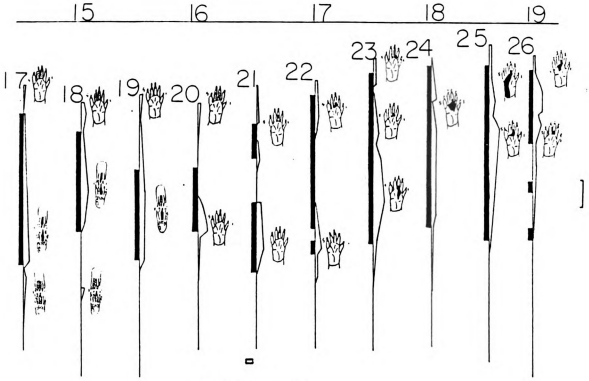
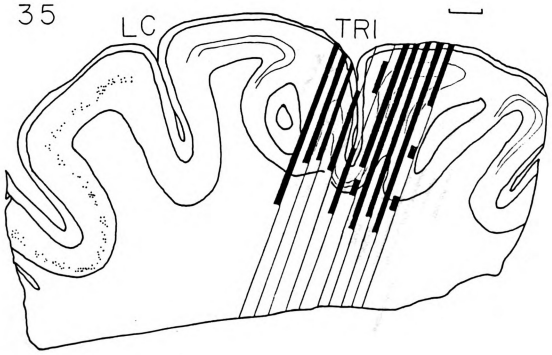


Figure 5-6.D



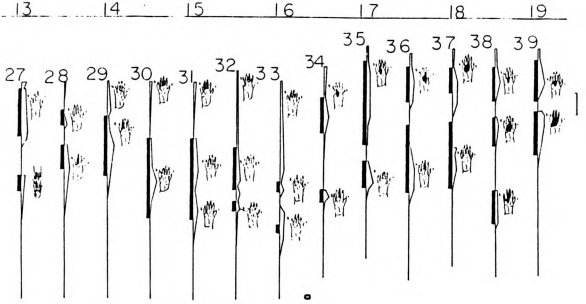
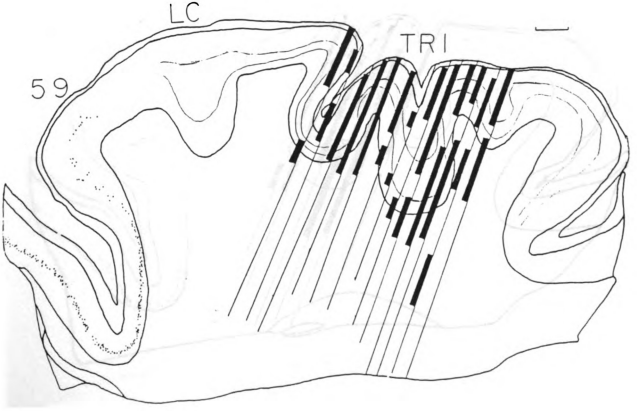


Figure 5-6.E



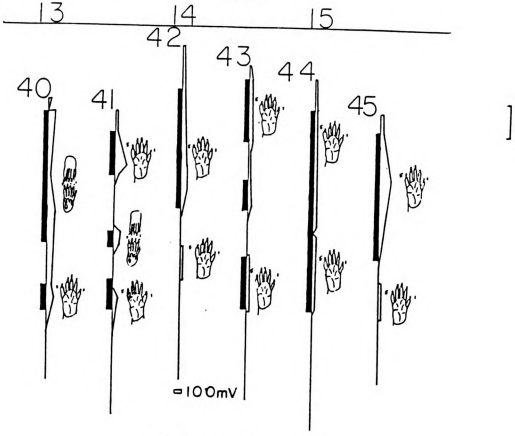


Figure 5-6.F

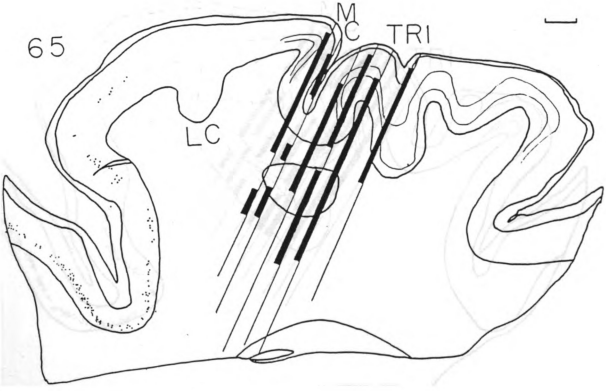


Figure 5-6.G

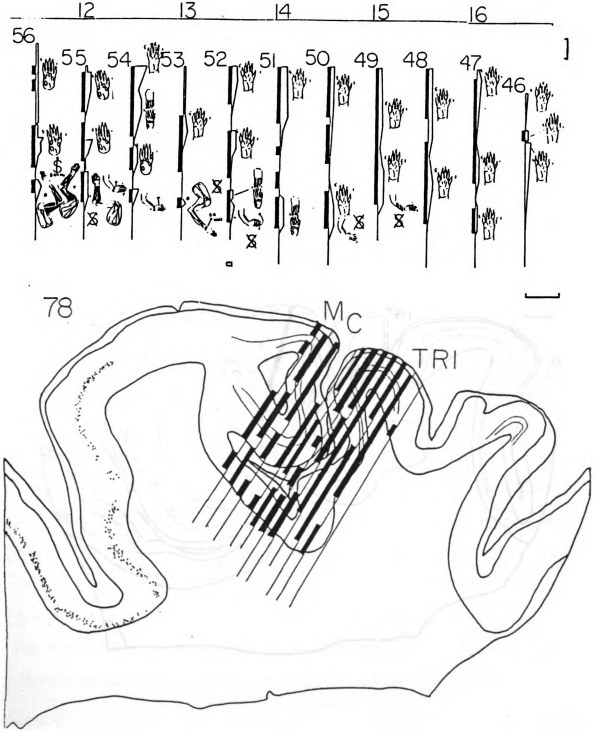
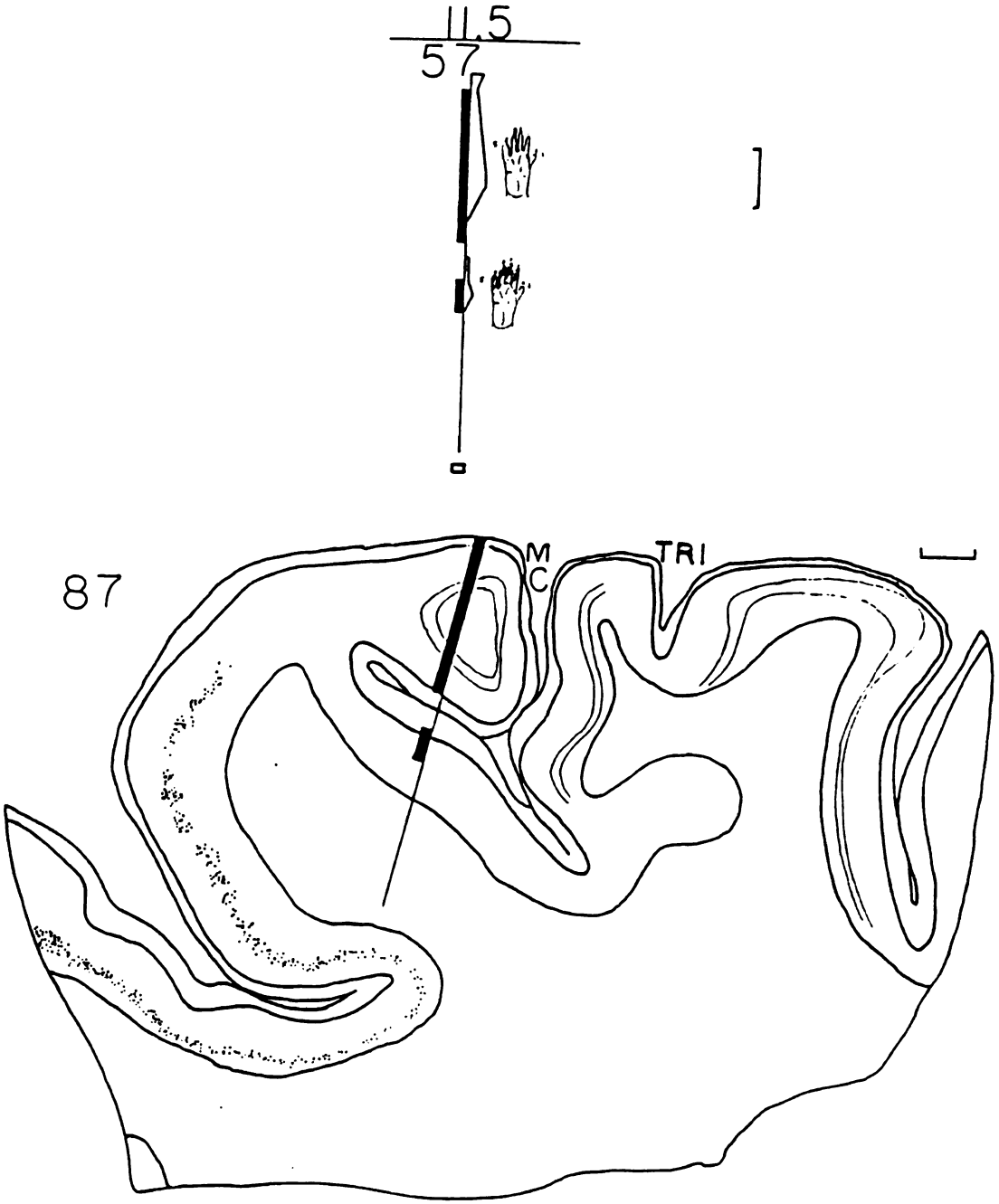


Figure 5-6.H



represented laterally and lateral palm medially in the TRI sulcus. Multiple proximal digit receptive fields evoked responses in the fundus region of the TRI sulcus (Figures 5-6.B,C). Distal antebrachial 100Hz stimulated muscle afferent responses were recorded in the anterior bank and fundus of the MC sulcus (Figure 5-6.G). 100Hz stimulation of flexors and extensors of the distal antebrachium convergently activated unit-cluster activity in this area.

In this animal the MC and TRI sulci were closely subjacent forming a very distorted convolution of the MC sulcus. The LC sulcus which could be visualized histologically, but could not be seen grossly as it was extremely shallow and smoothed by a thickened layer I.

Section 5.8: Results from Raccoon 84528

Fifty eight electrode penetrations forming twelve medial-lateral oriented rows mapped the entire MC sulcus and the medial LC sulcus which in this animal were continuous (Figures 5-7.A-N). The first row of penetrations was located anterior in the primary motor area (M-I), where evoked potentials were the slow wave (sw) type (see section 5.9 or see Sakai, 1980) regardless of whether they were of cutaneous or muscle origin (Figure 5-7.C). Units evoked along the anterior bank of the medial portion of the LC sulcus were elicited by stimulation of disjunctive receptive fields located on multiple digit and claw

Figure 5-7:

Fifty-eight electrode penetrations forming twelve medial-lateral oriented rows mapped the entire extent of the MC sulcus and a medial portion of the LC sulcus which were continuous in raccoon 84528. 5-6.A depicts a dorsolateral view of the mapped area in the left cerebral hemisphere. 5-7.B are drawings of the histologic sections at the level of each row of penetrations. 5-7.C-N are the figurine drawings for each row of penetrations, 5-7.C being most anterior with the rest sequentially more posterior. Photographs of the histologic sections from which the drawings were made are on the page opposite the corresponding figurine drawing. Anterior in Area 4 evoked cortical responses were of the slow wave type (Figures 5-7.C, D,E; and see Figure 5-9). Units evoked by 100Hz distal antebrachial muscle stimulation lay along the medial portion of the anterior bank of the LC sulcus (Figures 5-7.E,F,G) and lateral anterior bank of the MC sulcus (Figure 5-7). Heterogeneous distal digit receptive fields were represented on the posterior bank of the medial LC sulcus (Figures 5-7.C,D,E,F). There was somatotopic representation of muscle afferent responses along the anterior bank of the central sulcus. Hindlimb muscles represented in the posterior bank and fundus of the medial MC sulcus (Figure 5-7.H); forearm muscles along the lateral anterior bank of the MC sulcus near the fundus (Figures 5-7.G-K) and a small area on the medial anterior bank of the LC sulcus (Figures 5-7.E-H). Proximal muscles are represented caudally in kinesthetic cortex to distal muscles (see text).

84528

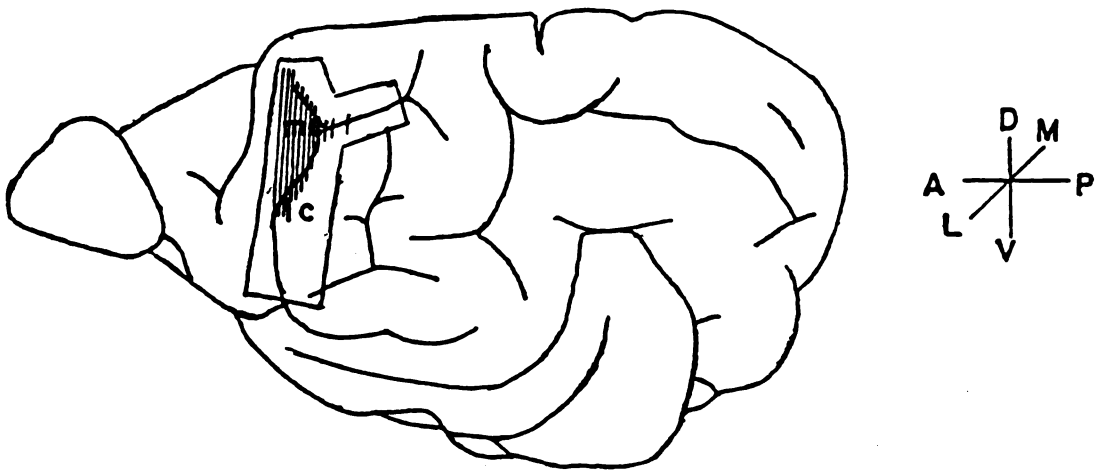
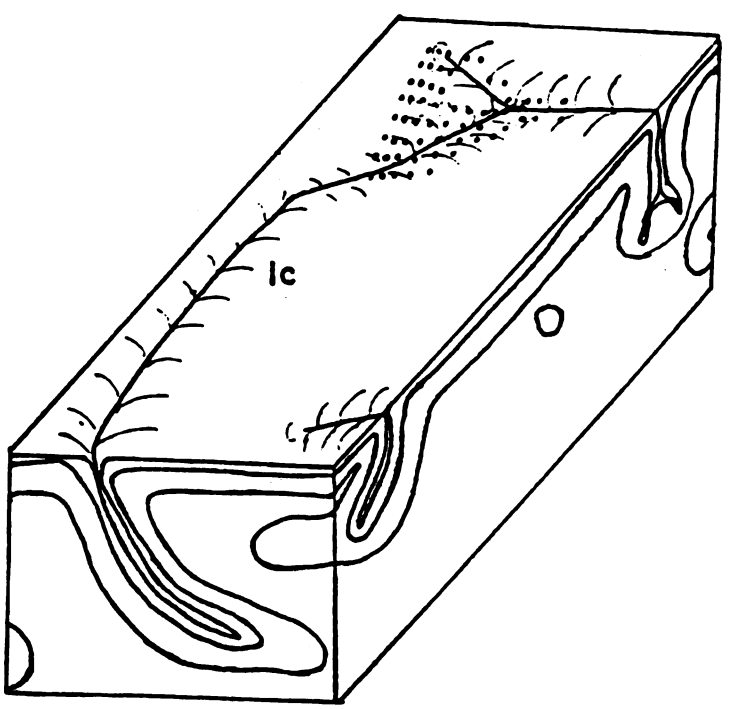
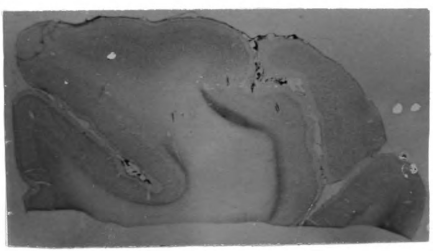


Figure 5-7.A





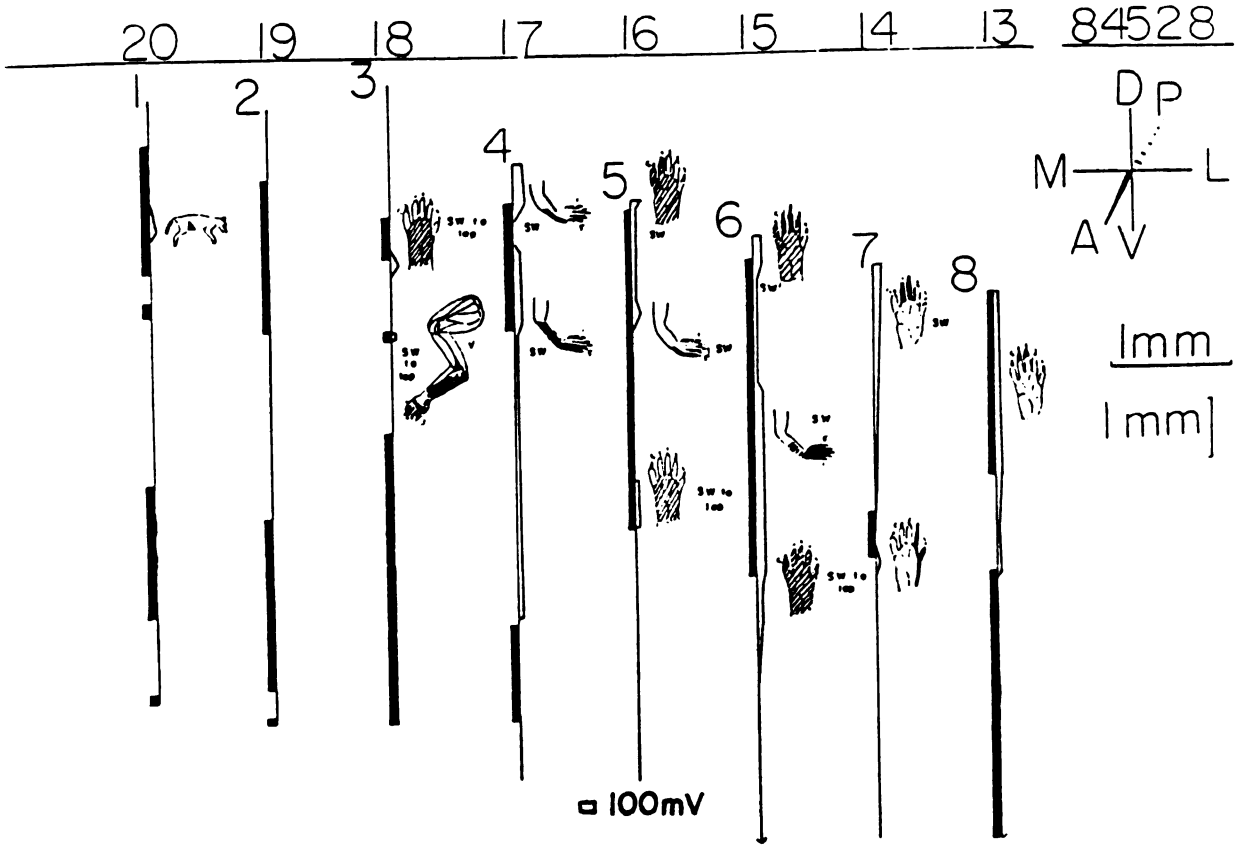

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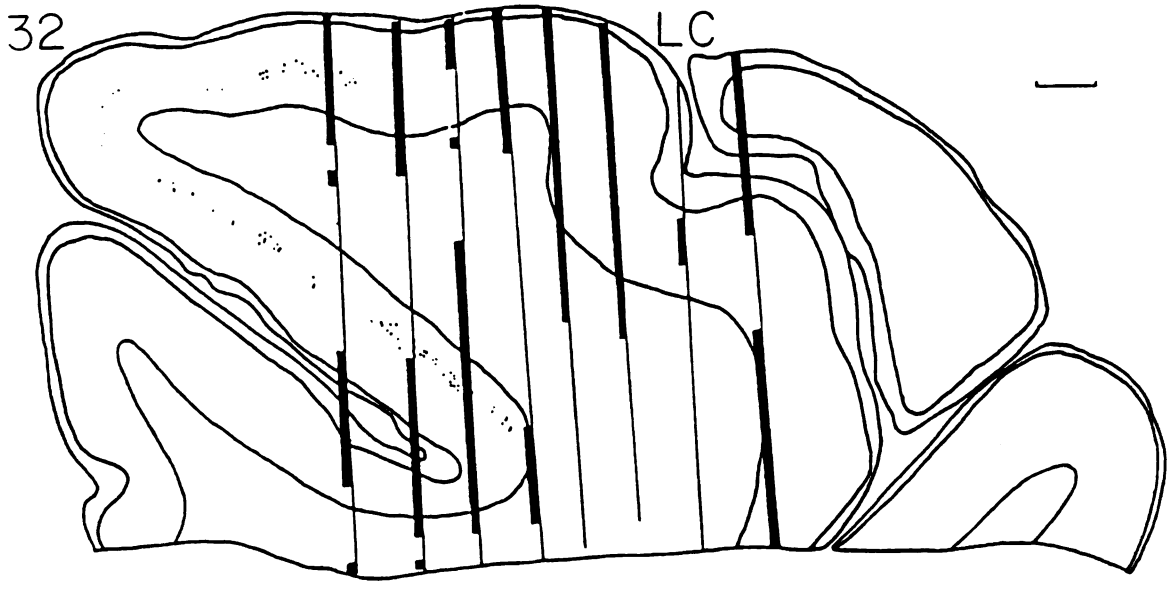
Figure 5-7.C.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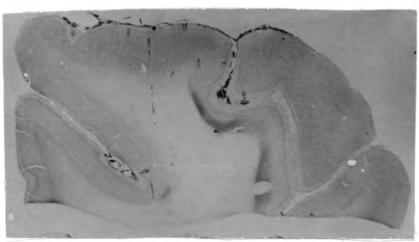
LC



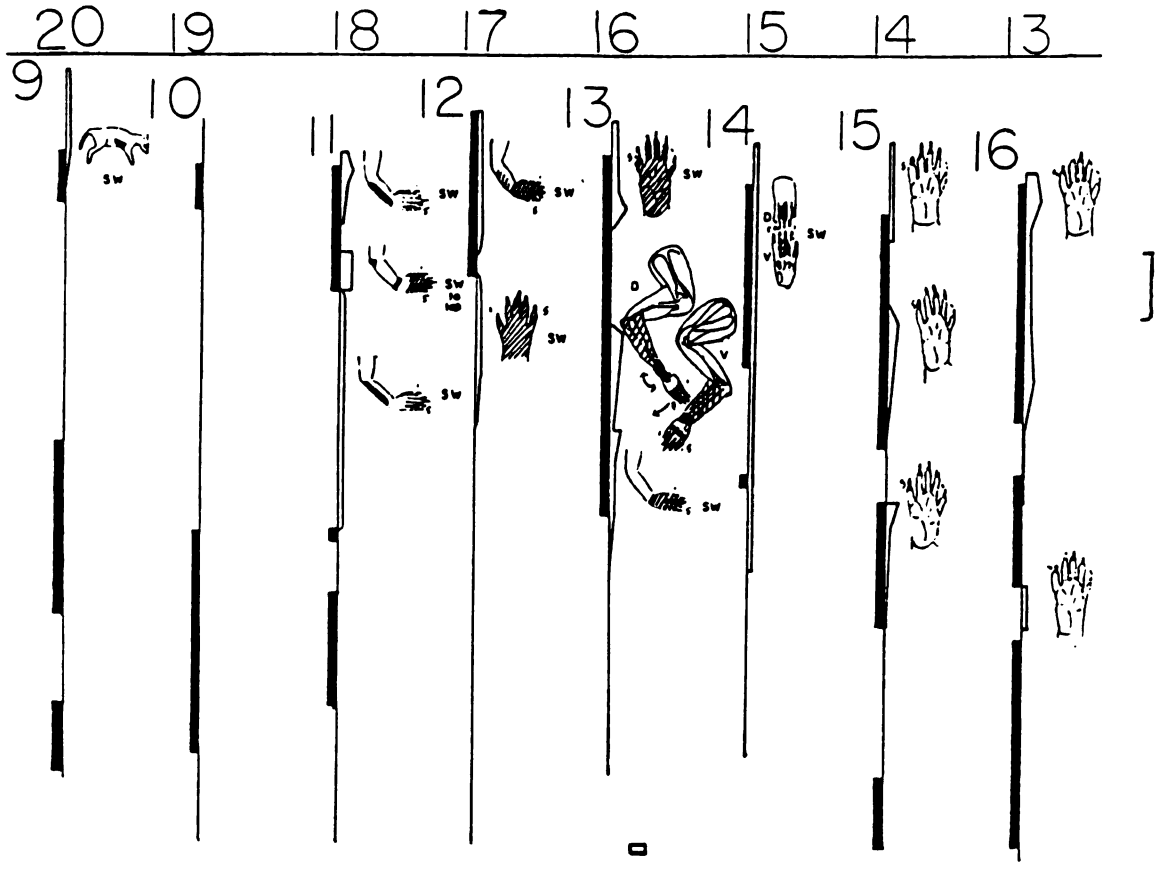
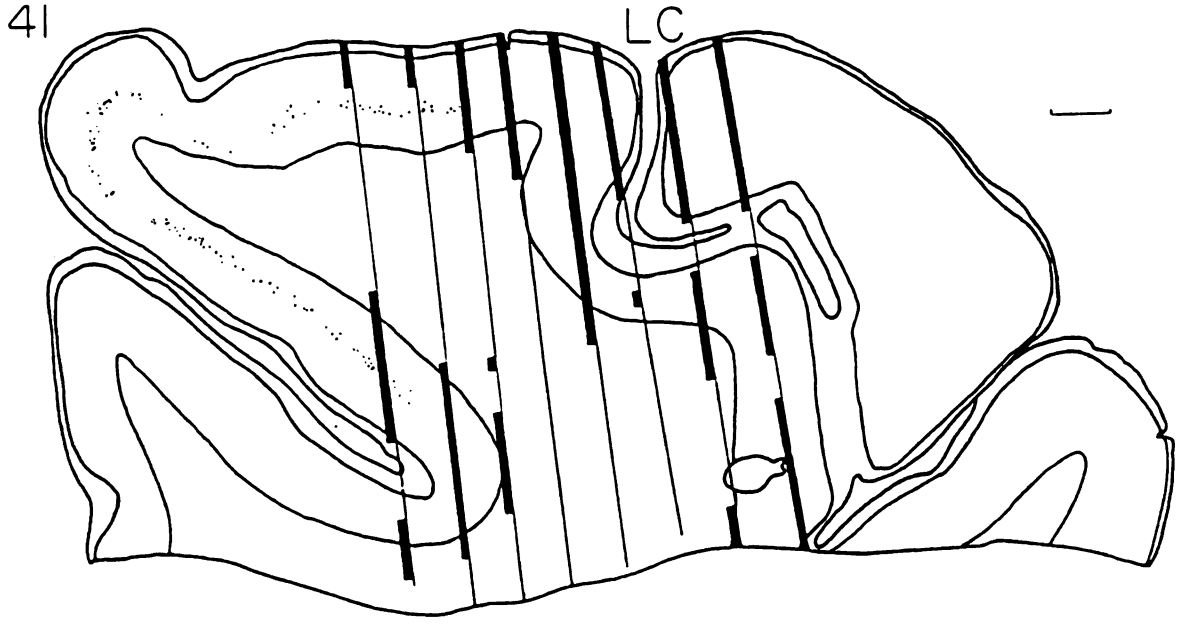
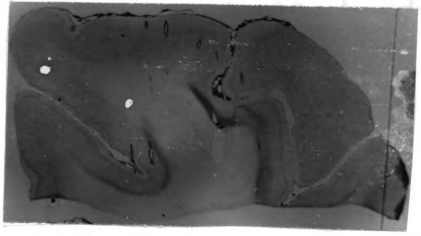


Figure 5-7.D





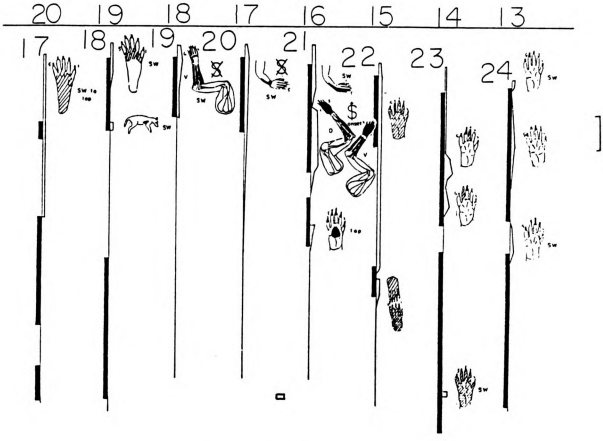
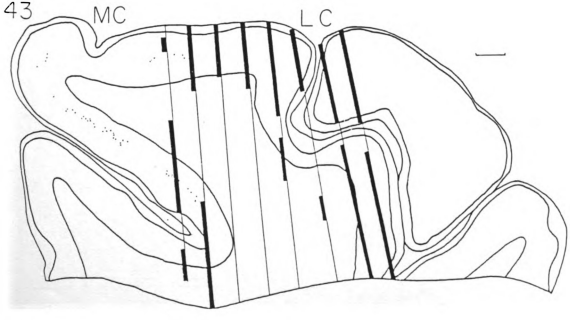
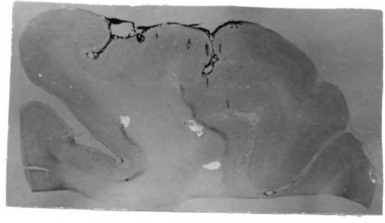
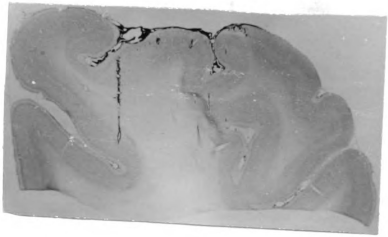


Figure 5-7.E







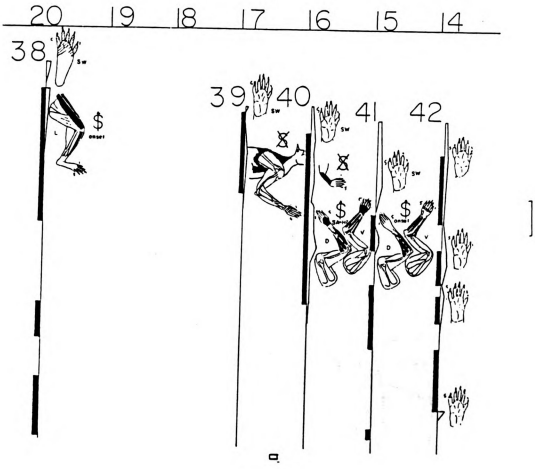
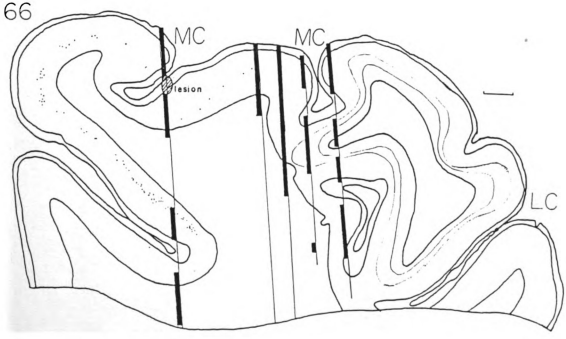
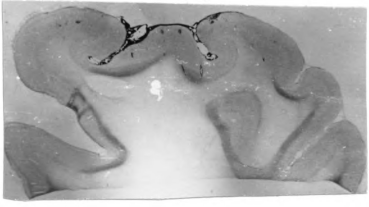


Figure 5-7.H





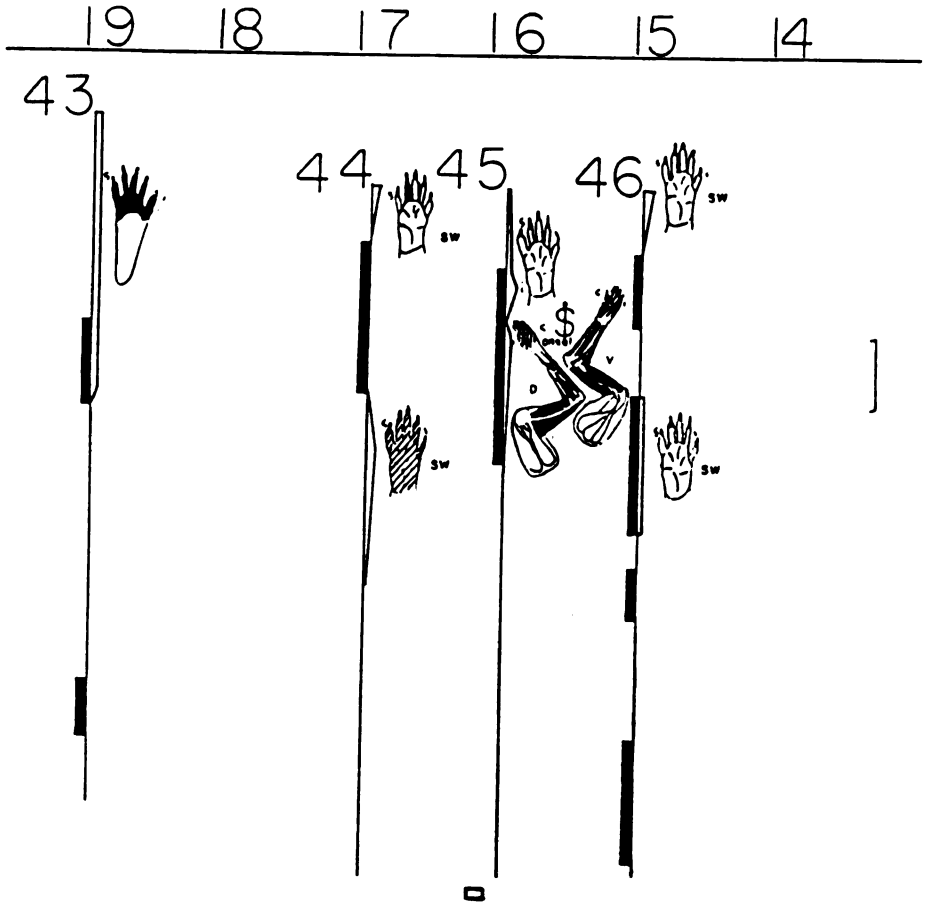
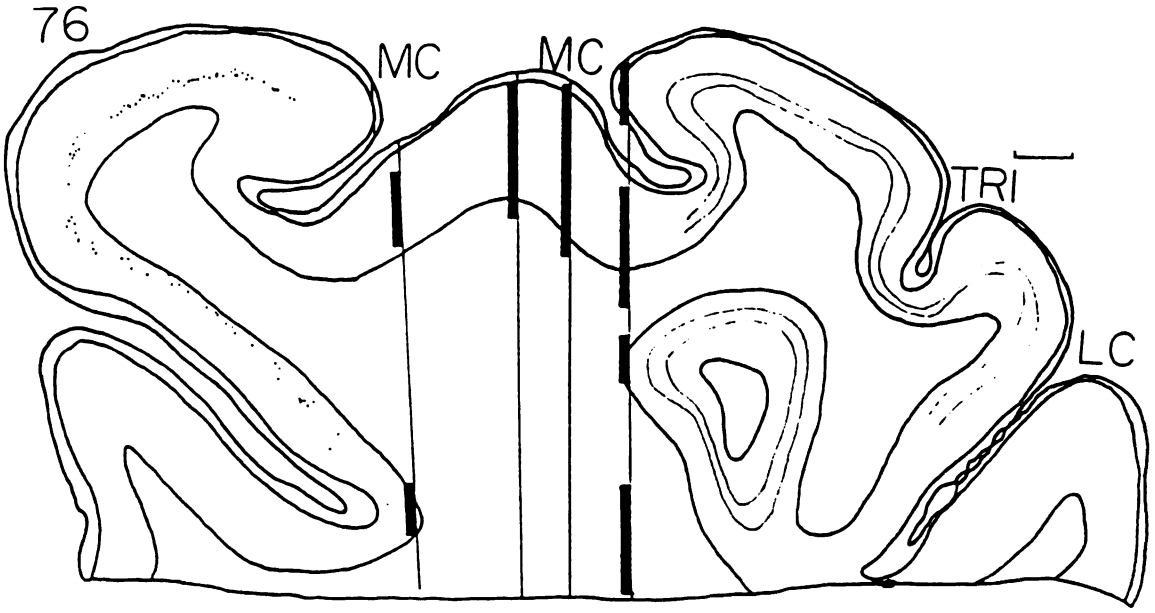
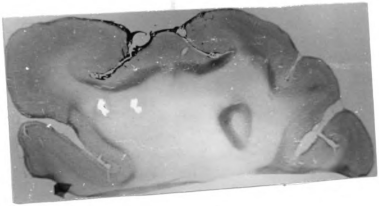


Figure 5-7.I





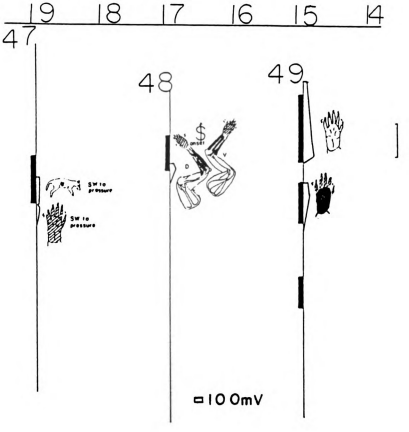

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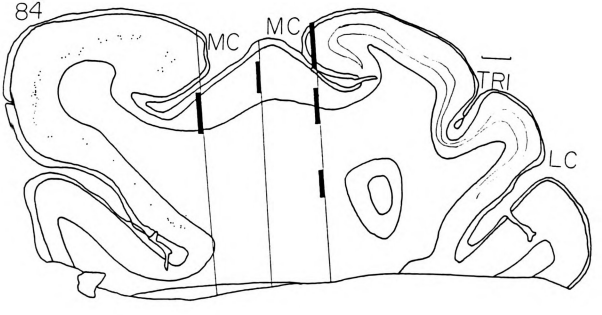
Figure 5-7.J


84
MC
MC
TRI
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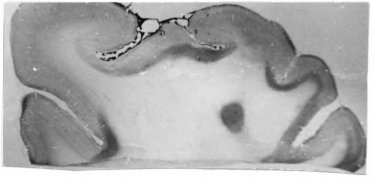


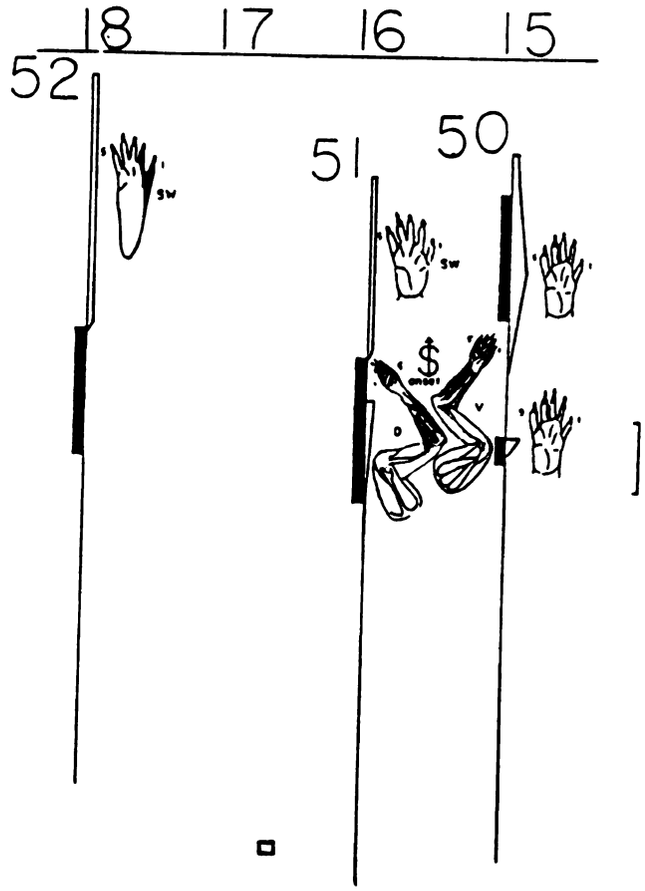
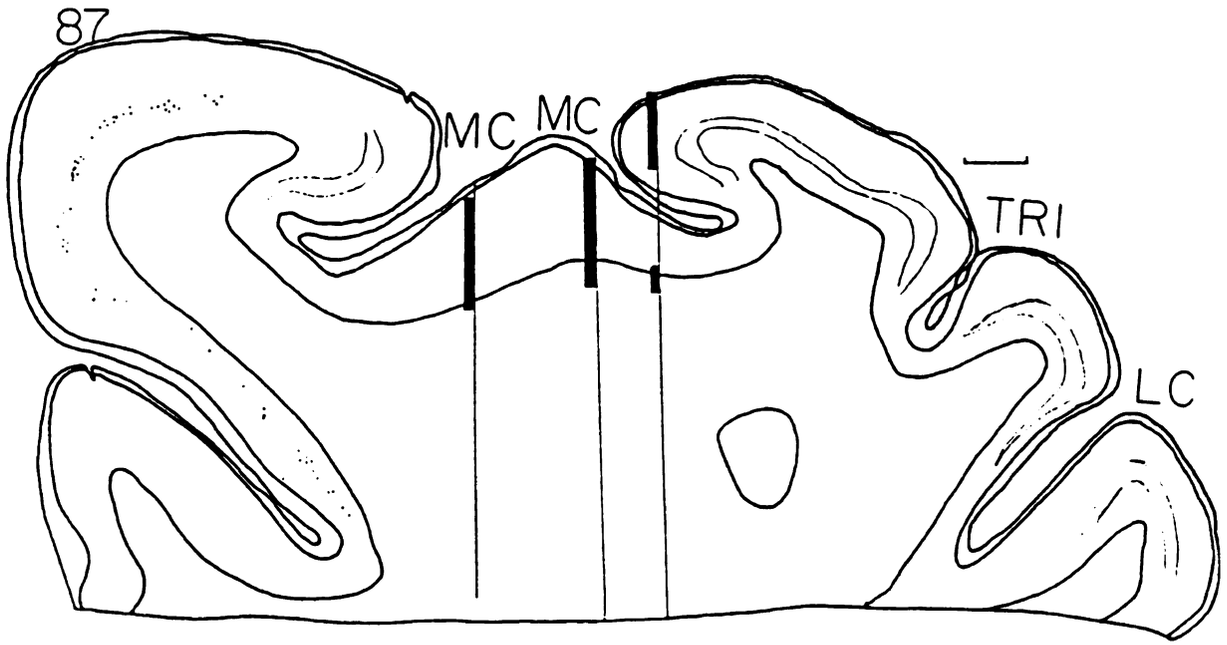
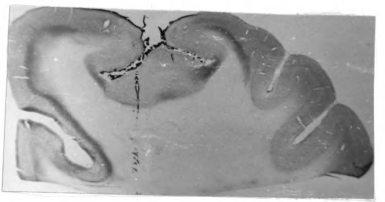
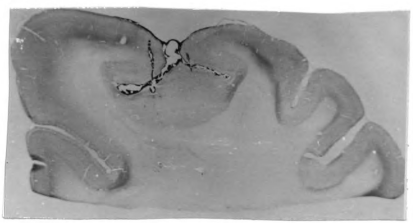


Figure 5-7.K







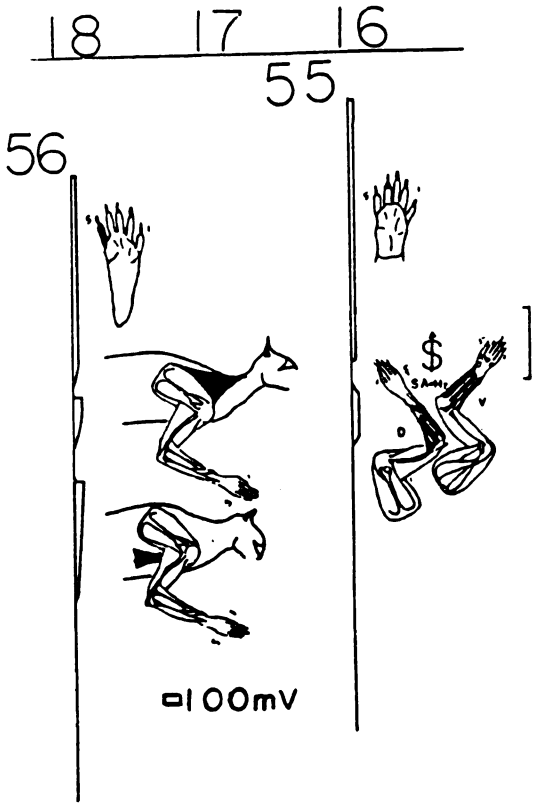
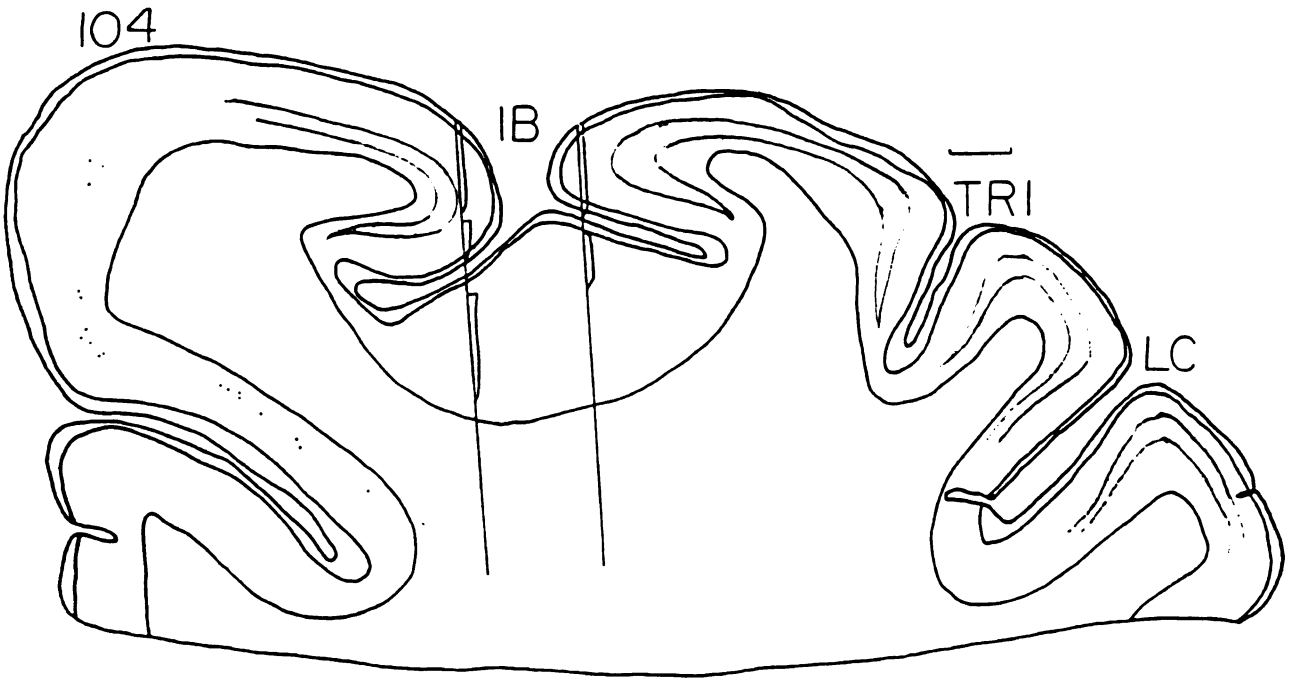
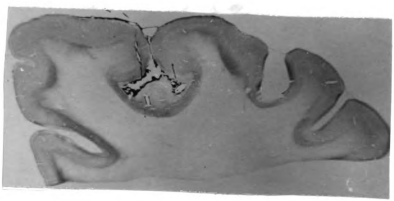


Figure 5-7.M





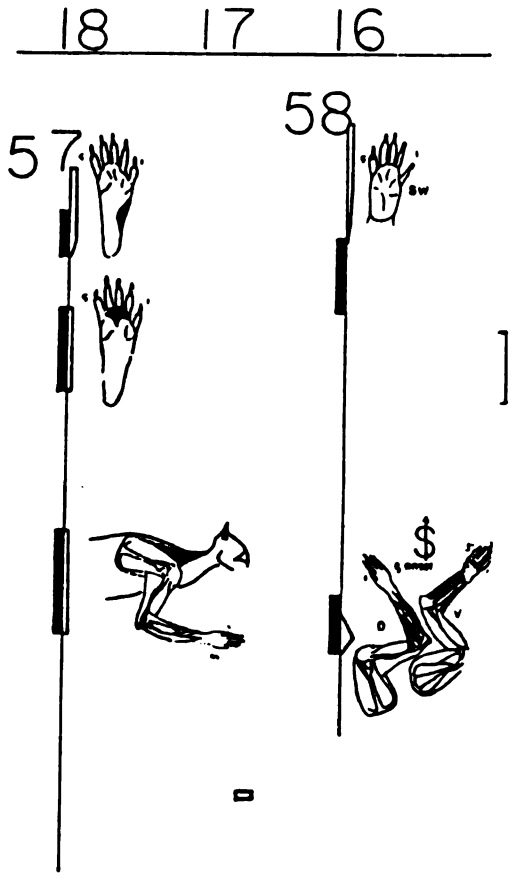
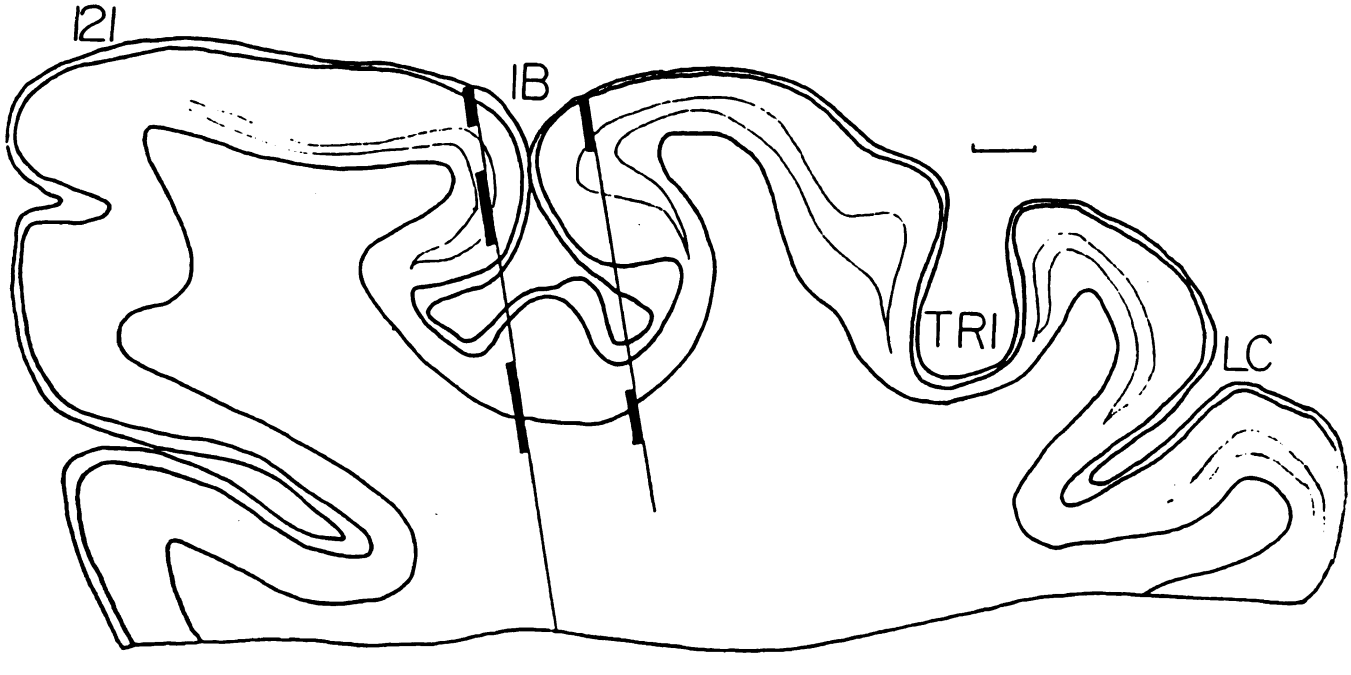


Figure 5-7.N



responses (Figures 5-7.C-G). Several 100Hz stimulated distal antebrachial muscle afferent responses were recorded in the fundus and anterior bank of the LC sulcus as the electrode advanced more closely to S-I (Figures 5.7,E-G).

The anterior bank of the MC sulcus lateral to the IB sulcus anterior represented 100Hz responsive evoked activity from flexor and extensor muscles of the carpus and digits (Figures 5-7.G-L). Scapular muscle representation (not 100Hz responsive) was located along the crest of the anterior bank of the MC sulcus, medial to the distal antebrachium muscle representation area (at the anterolateral margin of the IB sulcus, Figure 5-7.H). Proximal antebrachial muscles responses were mapped caudal to the scapular muscle responses, along the caudally extending tip of anterior bank of the MC sulcus which juts into the anterior IB sulcus (Figure 5-7.I). Evoked units to distal antebrachial muscles continued down the anterior bank of the MC sulcus into along the interfundic rise which is a continuation of the IB sulcus of the precentral gyrus (Figures 5-7.K-N). Evoked activity along the interfundic rise of the IB sulcus represented distal antebrachial muscles in an area lateral to scapular muscle representation. Muscle responses evoked within the IB sulcus were of relatively low amplitude compared to responses in the MC sulcus. Units on the lateral bank of the IB sulcus were evoked by stimulation of dorsal distal digits 4 and 5 on the

anterior and posterior bank, respectively. Distal antebrachium and scapulo-thoracic representations continue within the interfundic rise along its anterior two-thirds. Muscle responses within the IB interfundic rise, steadily diminish in response amplitude as recording loci were located further caudally from the MC sulcus (demonstrated in raccoon 84522, results not shown).

Section 5.9: Cortical Cytoarchitecture in the Muscle Response Zones, S-I and M-I

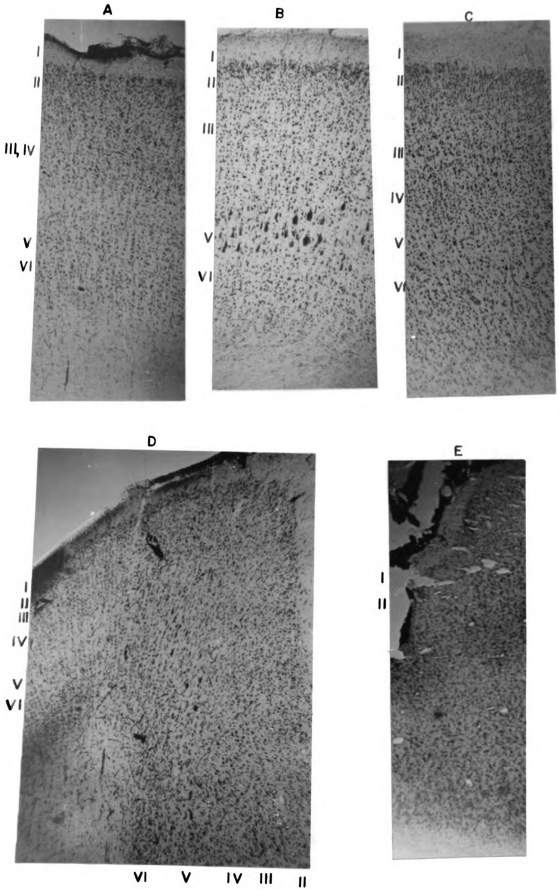
The anterior bank of the MC sulcus represents forearm muscles along its lateral arm, and hindlimb muscles along the fundus and posterior bank of its medial arm. In addition, distal forearm muscles and scapular muscles were mapped in the interfundic rise at the base of the IB sulcus. These three cortical areas (medial MC, lateral MC and IB bottom) all have unique cytoarchitecture when compared with each other, and with S-I or M-I.

S-I proper in the raccoon, between the central and ansate sulci, is most easily delineated by the presence of the cell free stripe of Baillarger in cortical lamina V. The inner granular layer (IV) and small pyramidal layer (III) blend together in a manner which makes it difficult to draw a boundary between them (Figure 5-8.A). Large pyramidal cells in layer V are sparse in S-I.

Area 4 can be distinguished histologically along the banks of the cruciate sulcus, not entirely coinciding with

Figure 5-8:

Photographs of the cytoarchitecture of five cortical areas are displayed on the opposite page.
A - primary somatic sensory cortex (10X); B - primary motor cortex (10X); C - the anterior bank of the MC sulcus in the distal antebrachial muscle representation area (10X); D - the posterior bank of the MC sulcus in the hindlimb muscle representation area (5X), arrows point to layer V pyramidal cells; E - the interfundic rise at the base of the IB sulcus (5X). Cortical layers I-VI are labelled where boundaries are apparent. Large layer V pyramidal cells are seen further caudally toward the medial MC sulcus posterior bank from M-1 through the fundus region to overlap the rostrally attenuating layer IV granule cells from S-1 (Figure 5-8.D), meeting the criteria of area 3a. Along the lateral arm of the MC sulcus kinesthetic responses on the anterior bank of the MC sulcus are in an area to which the large layer V pyramidal cells do not reach, some smaller layer V pyramidal cells are present (Figure 5-8.C). The interfundic rise within the IB sulcus lacks any distinctive cortical layering (Figure 5-8.E).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electrophysiologic M-I (Harden, et al., 1968). This cortical region is distinct because of the presence of large layer V pyramidal cells (Figure 5-7.B). Area 4 extends closer to S-I along its caudomedial boundary near the fundus of the medial MC sulcus as compared to its lateral boundary near the precentral gyral crest anterior to the LC sulcus (Hardin, et al., 1968; thesis findings). Layer IV granular cells are sparse to non-existent in M-I. The small pyramidal layer III comes to lie adjacent to an expanded layer V.

The anterior bank along the lateral arm of the MC sulcus appears as described by Johnson (et al., 1982). The stripe of Baillarger and the inner granular layer become attenuated in this region anterior to S-I glabrous forepaw representation. In this cortical region boundaries between all six cortical laminae can be more easily distinguished than in S-I proper (Figure 5-8.C). There are pyramidal cells in layer V, none of which reach the large size seen in layer V of area 4.

The hindlimb muscle representation area along the posterior bank and fundus in the medial arm of the MC sulcus presents yet another cytoarchitecture. In this region the cell free stripe and granular layer IV are attenuated as described for the lateral arm. Layer V pyramidal cells extend caudally from area 4 into this region, but are not of the magnitude found in area 4 (Figure 5-8.D). These layer V large pyramidal cells

come to overlie the attenuated layer IV granular layer in the fundus and posterior bank of the medial MC sulcus. This region is more similar to Area 3a of the rhesus monkey and cat (Jones and Porter, 1980).

The interfundic rise at the bottom of the IB sulcus also serves as a forearm muscle representation area. Below the molecular layer, only cortical layers II and VI can be histologically distinguished. Cortical laminae III, IV and V appear as a collection of poorly staining neuronal perikarya interspersed amongst an abundance of blood vessels (Figure 5-8.E). This cortical area has none of the distinctive cytoarchitectural characteristics noted in S-I, M-I or the other muscle representation areas. Evoked kinesthetic responses recorded in the IB interfundic rise were of weak amplitude (<50mV) or audible only.

Section 5.10: Evoked Cortical Responses in the Central Sulcus, M-I and S-I

During extracellular recording in the primary somatic sensory area cortical responses in the gray matter, evoked by stimulation of a cutaneous receptive field, were of the single unit or unit-cluster types (Figure 5-9.A). The single unit responses had one sharply defined peak measuring between 50-250μV in amplitude, or a few unit peaks separated by a minimum refractory period. Single unit responses are thought to be the recording

of the discharge of a single cortical cell, or small group of cells in a cortical column which are discharging simultaneously (Mountcastle, 1978). The distinction between single unit and unit cluster activity was made by the temporal relationship of unit peaks and amplitude shape of the complex evoked as an oscilloscope tracing to a given peripheral stimulus (see Figure 1A in Johnson, et al., 1974).

In this thesis unit cluster responses were identified as a complex of unit peaks, roughly uniform in amplitude (between 50-250μV), the complex less than 10msec in duration (Figure 5.9B). Unit cluster responses were recorded most often in both the kinesthetic area and primary somatic sensory area. In the kinesthetic cortical area, unit cluster responses were often superimposed on a slow wave response (Figure 5-9.B).

The "slow wave" cortical response associated with the primary motor area had a broad peak of amplitude 50-250μV and a duration of over 10msec. Slow wave responses often required a relatively strong peripheral mechanical stimulus to be evoked (see Figure 5-9.C). These evoked responses were recorded in both the cortical gray and white matter of an M-I cortical column. There appeared to be a longer latency between stimulus and evoked cortical activity of M-I responses when compared to responses in S-I (not quantified in this study; see Tanji and Wise, 1981). Likely, M-I responses evoked

Figure 5-9:

Photographs of oscilloscope tracings from mechanically evoked cortical responses in: S-I (a unit-cluster, 5-9.A), a kinesthetic response on the anterior bank of the MC sulcus (unit cluster riding a slow wave, Figure 5-9.B) and an area 4 response (a slow wave, Figure 5-9.C). Cortical responses in the kinesthetic area appear to have characteristics both similar to, and unique from, the cortical responses seen in S-I and area 4.

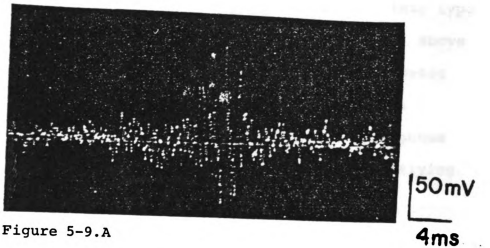


Figure 5-9.A

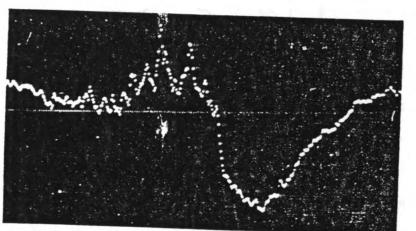


Figure 5-9.B

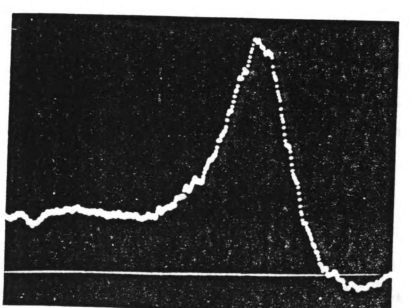


Figure 5-9.C

peripherally gain acess to motor cortex via intracortical relay from adjacent S-I (see Section 2.5.b.i). This type of response was also recorded in the white matter, above and below single unit responses in the primary somatic sensory cortical gray columns, usually evoked by a less well defined receptive field which was contiguous with the well defined receptive field of the underlying cortical column.

Units which are audible over an audio monitor but not necessarily visible on an oscilloscope as an evoked response meet the criterion of some investigators to distinguish somatic sensory cortical recordings (e.g. Adrian, 1943; Welker and Campos, 1963). "Audible only" responses were recorded in the interfundic rise within the IB sulcus, and also in layer 1 of S-I and M-I.

The increase in recorded background spontaneous activity when a microelectrode was placed in the cortical gray matter, as opposed to the white matter, is likely due to the increase density of neuropil elements in the gray matter about the nerve cell bodies and their dendritic arborizations. Spontaneous unit activity likely represents electrical responses of numerous neuropil elements, whereas fiber tracts having a lower density of conductive elements would be expected to exhibit lower spike activity (Johnson, 1968).

Since single unit and unit-cluster activity are recorded in granular cortex, they are likely in part

associated with the discharge of the expanded layer IV granular cells in response to incoming thalamic afferents volleys. Cortical units evoked by stimulation of kinesthetic receptive fields, recorded in the medial central sulcus, were of the unit-cluster (multi-unit) type superimposed on a "slow wave" response (Figure 5-9.B). Kinesthetic cortical responses appeared to be a composite of those evoked in S-I and M-I. Possibly both thalamic afferent volleys to layer IV and short corticocortical afferents contribute to the recorded unit-cluster response.

In the raccoon there is a somewhat loose relationship between cortical cytoarchitecture and the waveform of the evoked response. Single-unit responses were unique to the primary somatic sensory cortex in the sensory-motor area. Slow wave responses were the only response of the primary motor area (which does not perfectly coincide with area 4), but were also recorded in layer I of S-I and the white matter below S-I. Unit cluster responses were recorded in both S-I and the kinesthetic cortical areas of which there were several different cytoarchitectonic appearances.

SECTION 6: CONCLUSIONS AND DISCUSSION

Several general conclusions were made about raccoon sensorimotor cortical organization based on the findings in this thesis:

1. A cortical area responding to mechanical stimulation of forelimb and hindlimb muscles afferent is located between S-I and M-I in the entire MC, lateral LC and anterior 2/3 of the IB sulci of the raccoon. These cortical areas were designated kinesthetic cortex.

2. The raccoon kinesthetic cortical area is somatotopically organized with hindlimb represented medially in the posterior bank and fundus of the medial MC sulcus and an expanded distal forelimb muscle representation area laterally in the anterior banks of the lateral MC sulcus and medial LC sulcus, and along the lateral interfundic rise of the IB sulcus. Distal appendage muscles were represented anterior to proximal appendage muscles.

3. The cytoarchitecture of the fundus and posterior bank of the medial MC sulcus meet the cytoarchitectonic criteria area 3a of Hassler and Muhs-Clement. The rest of the kinesthetic cortical areas present unique cytoarchitectures whose appearance depends on which area is being considered.

4. 100Hz vibration of denuded muscle bellies is not a thorough means of exploring kinesthetic cortex. Some muscle responses could be evoked by manual manipulation of muscles when 100Hz stimulation gave no response (possibly originating in secondary spindle endings, fascial mechanoreceptors or tendon organs).

5. There is a fairly strict association between cytoarchitecture and waveform characteristics of evoked responses in S-1 (single-unit or unit cluster), and area 4 ("slow wave" responses), but

not kinesthetic cortex (a unit cluster riding a "slow wave") which has several cytoarchitectures.

6. A zone of heterogeneous receptive field projections with vague somatotopic organization exists: between the kinesthetic cortical area and M-I medially; traversing the gyral bridge area between the arms of the MC and LC sulci; and on the posterior bank of the LC sulcus between S-1 and M-1.

The significance of this research lies in providing further evidence that a kinesthetic cortical area exists between M-I and S-I, and that this is a general feature of mammalian somatic sensory cortical organization. The expanded distal antebrachial muscle representation within the raccoon kinesthetic cortical area alludes to an increased muscle spindle mechanoreceptor density in these muscles as compared to those of the hindlimb and axial body (no reported direct evidence exists to support this at this time). The enlarged distal antebrachial muscle representation area bears a relationship to the enlarged forepaw glabrous digit representation seen in raccoon S-I. Both are related to the specialized forepaw tactile exploratory behavior of the raccoon. Primary muscle spindle responses were associated more with the distal antebrachial muscles than proximal antebrachial or hindlimb muscles. Possibly there is a greater density or primary muscle spindle endings in muscles related to the fine flexions and extensions of the forepaw digits, and a greater density of secondary spindle endings in muscles which assume postural roles. The plantigrade stance of the

raccoon on his hindlimbs allows a greater freedom of forearm movement, more similar to that of primates, than are the non-plantigrade dog or cat.

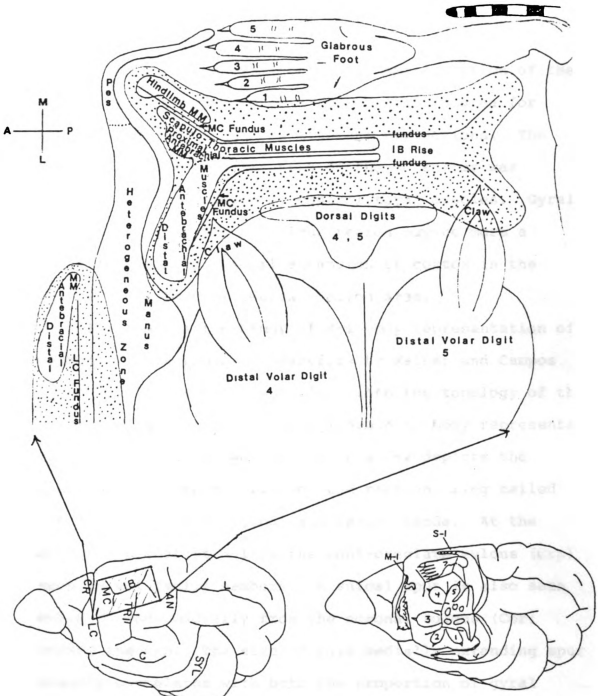
Section 6.1: What is the Extent and Topology of the Kinesthetic Representation Area Anterior to S-I in the Raccoon?

Muscle representation areas were mapped in the following cortical regions: 1) the anterior bank of the LC sulcus at its medial terminus; 2) the anterior bank of the lateral arm of the MC sulcus not including its lateral tip; 3) the fundus and posterior bank of the medial arm of the MC sulcus, each being successively more medial; 4) the anterior two-thirds of the inter-fundic rise within the IB sulcus and the continuation if its anterior end, as the anterior bank of the MC sulcus at the level of the IB sulcus (see Figure 6-1).

In the cat electrophysiologic area 3a lies in a region about the post-cruciate dimple (analogous to the primates' central sulcus) in an ovoid shaped area (Dykes, et al., 1980). Rhesus monkey forearm muscle afferent responses are evoked in the lateral portion of the anterior bank of the central sulcus between the forearm representation areas in M-I and S-I. Hindlimb muscle responses are medial to those of the forearm along the fundus and anterior bank of the central sulcus (Jones and Porter, 1980). These observations along with the mapping results

Figure 6-1:

A composite map of the muscle afferent zone (kinesthetic cortex) and zone of heterogeneous projections (shown above) along the anterior border of S-I. In this conceptual drawing, the MC, LC and IB sulci are unfolded so that responses on their banks (the dotted areas) may be displayed. Kinesthetic responses are located along the MC sulcus on the anterior bank in the lateral arm and the fundus and posterior bank of the medial arm; the anterior bank of the LC except its medial terminus and the anterior two-thirds of the interbrachial sulcus. The zone of heterogeneous projections extends along the deep posterior bank of the LC sulcus, across the gyral bridge area and lateral tip of the MC sulcus continuing as a narrow zone anterior to the glabrous hindfoot representation area of S-I. Two drawings of the raccoons' left cerebral hemisphere are depicted at the bottom of the figure, showing the location of S-I and M-I (bottom right) and some major sulci (bottom left). Sulcal abbreviations: CR = cruciate, LC = lateral central, MC = medial central, IB = interbrachial, SYL = sylvian, C = coronal and AN = anssate.


5
4
3
2
1
Glabrous
Foot
Pes
Hindlimb MM
MC Fundus
Scapular
Thoracic Muscles
fundus
IB Rise
fundus
Muscles
Antebrachial
Distal
MC
Fundus
Dorsal Digits
4 , 5
Claw
Heterogeneous Zone
Manus
Distal Volar Digit
5
Distal Volar Digit
4
M
A
P
L
S-I
M-I
3

of anterior S-I in the raccoon lead to Johnson's (et al., 1982) speculation that the muscle projection zone is consistently associated with the fundus and anterior bank of the central sulcus.

In this thesis research only a small portion of the medial LC sulcus served as a representation area for distal antebrachial muscle afferent projections. The majority of the anterior bank of the LC sulcus was "silent" to stimulation of contralateral muscles. Gyral configuration in the LC sulcus region may be more a consequence of functional expansion of cortex in the S-I glabrous forepaw representation area.

The comparative study of S-1 body representation of members in the family *Procyonidae* by Welker and Campos (1963) yields tremendous insight into the topology of the borders of S-1 and their relationship to body representation and total body weight. Figure 6-2 depicts the somatotopic representation of the raccoon, ring tailed cat, kinkajou, coati mundi and lesser panda. At the anterior border of S-1 is the post-cruciate sulcus (Crp) seen in all family members. A sulcal spur is also seen which extends medially from the coronal sulcus (Cor) toward the Crp. The size of this medially extending spur roughly correlates with both the proportion of gyral area in S-1 devoted to forepaw representation, and total body weight of the species. In the raccoon, the heaviest member for total body weight (ave. 8kg) of the family,

Figure 6-2:

A drawing taken from Welker and Campos (1963) depicting the somatotopic representation of body surface in S-I of members of the family *Procyonidae*. The anterior border of S-I is demarcated by the presence of the anterior arms of the pericruciate sulcus (Crp) and a medial spur (LC) off the coronal sulcus (Cor) in all but the ring tailed cat. The size of the medial coronal spur appears to correlate with the proportion of S-I which topologically represents the glabrous forepaw, being smallest in the ring tailed cat, larger in the lesser panda and larger still in the kinkajou. In the raccoon the pericruciate anterolateral arm and the dramatically enlarged medial coronal spur (LC) inconsistently meet to grossly form an analog of the primate central sulcus (see Figure 6-3). Because kinesthetic evoked cortical responses lie in the raccoon pericruciate (Crp = MC) anterior sulcal bank, and not on the majority of the LC anterior bank, and because the pericruciate sulcus separates S-I and M-I anatomically, it is proposed that the pericruciate sulcus of *Procyonidae* is analogous to the primate central sulcus. It is also proposed that the raccoon LC sulcus is an enlarged medial spur off the coronal sulcus, in some way a consequence of the gigantism of glabrous forepaw representation in S-I.

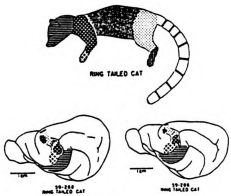


Figure 4

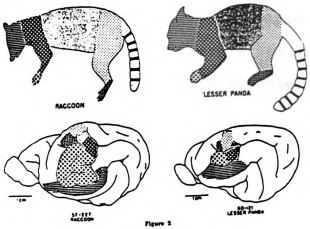
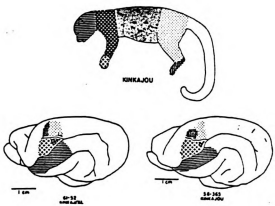


Figure 2



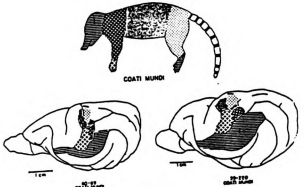
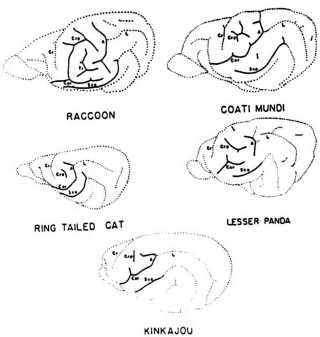


Figure 3

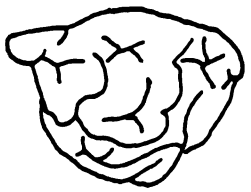


the medial spur of the coronal sulcus reaches its greatest size becoming continuous of closely overlapping the Crp. The raccoon also displays the greatest enlargement of forepaw representation of members in this family (see Figure 6-2). The kinkajou (2kg) had a noticeable medial coronal spur and large forepaw representation area, compared to the ring tailed cat (1kg) which had not spur and smaller forepaw representation. It would appear that the post-cruciate sulcus is present more consistently in the family *Procyonidae* than is the medial spur of the coronal sulcus and possibly is the homologue of the primate central sulcus separating S-1 and M-1. The results of this thesis, that the majority of the raccoons' kinesthetic cortical responses are located in the MC sulcus and medial tip of the LC sulcus while the majority of the anterior bank of the LC sulcus is silent to mechanosensory stimulation lend support to this supposition.

The high degree of variability of depth and course of the LC sulcus between individual raccoons as compared to the consistency of the position and depth of the MC sulcus is also interesting in light of electrophysiological findings (see Figure 6-3). Within the majority of the LC sulcus cortical responses were not evoked, while the MC sulcus was rich in evoked responses. Perhaps the MC sulcus is serving a functional role, while the majority of the LC sulcus (medial spur of the coronal sulcus)

Figure 6-3:

The drawings depict the left cerebral cortical surface of the first eight subjects in this study. Below is the drawing of an "average" raccoon cerebral cortex with sulci labelled. The continuity of the MC and LC sulci is complete in only one of the specimens. When an incomplete linkage between the medial LC and lateral MC arms occurs, the gyral bridge region is formed. The LC sulcus appears to be unrelated in the distance of its medial extent and anterior-posterior displacement with respect to any forming any continuity with the MC sulcus.



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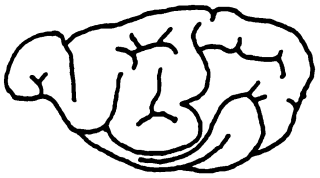

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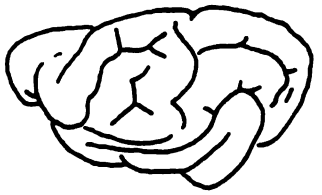

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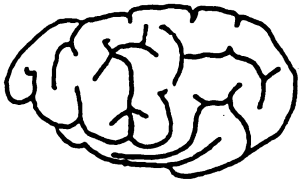

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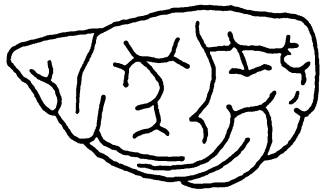

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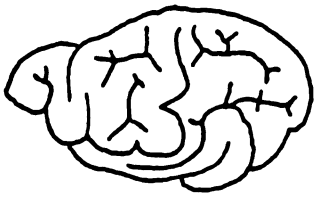

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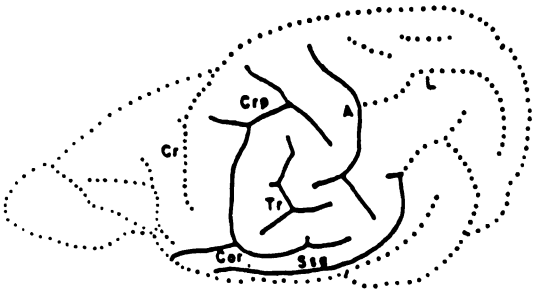

RACCOON

exists as a consequence of variable adjacent forepaw gyral expansion. This alludes to two principal determinants of sulcal folding at the anterior border of S-I in the raccoon: 1) a functional sulcal folding associated with a particular type of mechano-sensory afferent projection (e.g. the MC sulcus and the muscle afferent projection zone); 2) sulcal folding as a consequence of adjacent gyral expansion in the region of the glabrous forepaw representation of S-I (e.g., the majority of the lateral portion of the LC sulcus). In one animal in this study (84521) the LC sulcus was extremely shallow and could not be seen grossly, while the MC sulcus was present in its usual position and depth. Fissurization of the brain in general is known to vary with body weight of species with a family, also (Welker and Campos, 1963).

Section 6.2: What is the Somatotopic Organization of the Muscle Afferent Representation Area Anterior to S-I in the Raccoon?

The majority of the muscle afferent representation area received convergent projections from flexors and extensors of the carpus and digits. 100Hz stimulation of the distal antebrachial muscles evoked unit cluster responses in the following cortical areas mapped: 1) the anterior bank of the LC sulcus at its most medial terminus; 2) the anterior bank of the entire lateral arm

of the MC sulcus except its most lateral terminus; 3) the lateral half of the anterior two-thirds of the interfundic rise within the IB sulcus. Proximal antebrachial muscles (scapulo-humeral) project convergent information to a small portion along the anterior bank of the medial MC sulcus, just medial to the rostral extent of the IB sulcus.

Convergence in this thesis means that at a particular locus cortical unit cluster was evoked by stimulation of any muscle in a group of muscles around a common joint, or stimulation of skin overlying the group of muscles. Kinesthetic cortical representation was organized such that scapulo-thoracic muscle representation began medial to that of the proximal antebrachial muscles and extended caudally along the medial half of the anterior two-thirds of the interfundic rise within the IB sulcus. Hindlimb muscle afferent representation mapped along a small area of the anterior bank of the medial arm of the MC sulcus, adjacent to the scapular muscle representation area. Distal hindlimb muscles were high on the MC bank while proximal hindlimb muscles were deeper in the fundus of the sulcus.

The somatotopic distribution of muscle afferent projections in the raccoon form a procyonculus oriented similarly (though less well delineated) as that found in S-I proper. Hindlimb muscle representation lies medial to forearm muscle representation, and the appendages

appear to be pointing rostrally (a summary diagram is shown in Figure 6-1). This is the same as the orientation of the somatotopic distribution of muscle afferent projections described in area 8a of the cat (Dykes, et al., 1980) and the rhesus monkey (Kaas, et al., 1979).

The high degree of convergence of projections from muscle groups which act about a common joint(s) was noted in this study. This was also reported for forearm muscle afferent projections to area 3a in the cat (Oscarsson, et al., 1969), and in the feline thalamus (Andersen, et al., 1966). Such convergence of muscle input has been denied by other authors (cat: Landgren and Silfvenius, 1969; rhesus monkey: Phillips, et al., 1971). In the present study the technique of extracellular recording may appear to record convergent muscle afferent projections (as unit cluster responses) where single cell recording may show a little convergence of muscle groups. Extracellular recording would likely yield cortical responses more reflecting the overall activity in a given cortical column when compared to single cell intracellular techniques.

Convergence of muscle and cutaneous receptive fields which overlap in the periphery, was recorded in virtually all areas receiving muscle afferent input. This was reported in the cat (Oscarsson, et al., 1965; Silfvenius, 1970) where stimulation of cutaneous nerves could evoke cortical responses in area 3a of lower amplitude and

longer latency than the muscle inputs with which they converged. This was refuted by Dykes (et al., 1980) who reported less than 5% of units in feline area 3a could be evoked by cutaneous stimulation. Similarly, convergence of cutaneous and muscle inputs to area 3a has been reported in the monkey (Heath, et al., 1976).

Section 6.3: Is 100Hz Vibratory Stimulation of Muscles a Thorough Means of Mapping Kinesthetic Cortex?

The completion in this study of mapping the kinesthetic projection zone in anterior S-I of the raccoon required utilization of both 100Hz vibratory stimulation and direct mechanical manipulation (stroking and tapping of denuded muscles with nondonductive materials) to elucidate the entire zone of muscle afferent cortical responses anterior to S-1. The 100Hz vibratory method of stimulation of primary endings in muscle spindles (Goodwin et al., 1972a,b; 1972c) was utilized to map area 3a in monkeys by several authors (Phillips, et al., 1971; Lucier, et al., 1975; Hore, et al., 1976). The reason for utilizing this type of stimulation was to remove any ambiguity as to the origin of "deep" peripheral receptive fields, and unnatural nerve stimulation as in the dissected nerve preparation studies.

Not all evoked muscle responses arose from primary endings in muscle spindles (according to currently

accepted criteria; M.C. Brown, et al., 1967). For instance the scapulo-thoracic muscles when stimulated with 100Hz vibration were incapable of evoking cortical activity in the areas where they were represented. Mechanical stimulation of the denuded scapulo-thoracic muscles produced responses in the kinesthetic cortex which fit nicely into a somatotopic representation of muscle afferent projections. These muscle responses not stimulated by 100Hz vibration likely originated in secondary muscle spindles, fascial mechanoreceptors or golgi tendor organs. Proximal antebrachial and hindlimb muscles were not usually 100Hz responsive, these muscles subserving a postural role and not fine tactile exploratory manipulations which might require the feedback of primary spindle endings about dynamic movements. Primary muscle spindles may be more densely populous in muscles utilized for tactile exploration and secondary spindles more populous in muscles functioning in a postural role.

Section 6.4: What are the Cytoarchitectural Features of the Kinesthetic Cortical Area Anterior to S-I in the Raccoon?

As noted by Johnson (et al., 1982) the most consistent cytoarchitectural feature which localizes the zone of muscle afferent projections is the caudally adjacent attenuation of the cell free stripe of Baillarger. However, this same attentuation of the cell free stripe occurs in the fundus of the entire extent of the LC

sulcus, while kinesthetic responses were only recorded at its most medial terminus.

The banks of the medial and lateral arms of the MC sulcus differ cytoarchitecturally from each other, as well as from the interfundic rise within the IB sulcus. Each of the three kinesthetic zones (the anterior bank of the medial LC and lateral MC sulci, the fundus and posterior bank of the medial MC and the interfundic rise of the IB sulcus) are distinct from S-I and Area 4 as well. The same conclusion must be drawn in this study as that of Jones and Porter (1980) and Johnson (et al., 1982): no exclusive cytoarchitectural criteria can be assigned to the area which is electrophysiologically defined as area 3a. Each of the three kinesthetic areas presents a unique cytoarchitectonic appearance.

Similar to the results reported in the rhesus monkey (Jones and Porter, 1980), the raccoon hindlimb kinesthetic area seems to correspond to the caudal extent of the giant layer V pyramidal cells. Unlike the monkey, the raccoon hindlimb muscle afferent zone contains a thinned granular layer IV extending cranially from S-I proper which comes to overlie the caudally extending layer V giant pyramidal cells from area 4. Therefore in this region of the raccoon kinesthetic zone the cytoarchitectonic criteria of area 3a are met (the posterior bank and fundus of the medial arm of the MC sulcus).

The zone of muscle afferent projections extends along the interfundic rise at the bottom of the IB sulcus which is a cortical area of polymorphous architecture (when viewed in the frontal plane). In the interfundic rise the molecular layer 1, the granular layer II, and the polymorphous layer IV are distinct. Layer III and IV contain poorly staining stellate shaped cells and an abundance of small blood vessels. In a previous section, speculation as to the functional correlation between the MC sulcus and the zone of muscle afferent projections was stated (Johnson, et al., 1982). It was later speculated in that section that the LC sulcus occurs possibly as a consequence of the gyral expansion of the S-I glabrous forepaw representation. Combining these two ideas a third is formed which may explain the presence of kinesthetic projections in the IB sulcus. Gyral expansion in the glabrous forepaw representation area may have encroached upon the functionally positioned MC sulcus, distoring its shape and giving rise to the interfundic rise in the IB sulcus. This may have drawn the kinesthetic projection zone into the base of the IB sulcus.

Section 6.5: The Zone of Heterogeneous Projections

As a consequence of the systematic mapping of the anterior border of S-I, limits were also delineated for the zone of heterogeneous projections described by

Johnson (et al., 1982). Cortical responses from the dorsal surface of the digits and hand, and multiple digit and claw responses were evoked on the posterior bank of the LC sulcus (Figure 5-1.B), the gyral bridge area (Figures 5-2.B-E; Figures 5-3.B-E; Figures 5-4.B-D), lateral to the lateral terminus of the triradiate sulcus (Figures 5-5.B,C) and the lateral terminus of the MC sulcus (Figures 5-3.B,C). Similar dorsal toe and foot responses, and multiple glabrous toe responses were mapped at the anterior edge of S-I rostral to the glabrous foot representation area (Figures 5-4.F-H; Figures 5-6.I,K). No projections from heterogeneous receptive fields proximal to the hand were recorded. A crude somatotopic distribution within the zone of heterogenous projections exists with foot representation medial (anterior to the medial arm of the MC sulcus) and forepaw representation lateral (in a narrow band surrounding the anterior border of the S-I glabrous forepaw representation). This extent of the heterogeneous zone was hypothesized by Johnson (et al., 1982) and has been confirmed by this study.

The forepaw heterogeneous zone was localized to the posterior bank of the LC sulcus, the gyral bridge between the MC and LC sulci, the lateral terminus of the lateral arm of the MC sulcus and the crest of the anterior bank of the lateral arm of the MC sulcus. All these areas contain an expanded granular layer IV and external stripe

of Baillarger (more attenuated medially at the crest of the anterior MC) which places this portion of the heterogeneous zone in cytoarchitectonic S-1 of the raccoon. Electrophysiological responses in this zone were of the unit cluster type.

The foot heterogeneous responses were confined to two small regions, one located anteromedial to the glabrous foot representation area. In this region evoked responses were of the unit-cluster type, and the cytoarchitecture is similar to that of S-I. The foot heterogeneous zone continued along the anterior crest of the medial arm of the MC sulcus where the evoked waveform became characteristically "slow wave" and the cytoarchitecture was similar to area 4.

Section 6.6: Summary Statement

This thesis has shown, using stimulation of muscles and related tissues dissected free of overlying skin, that there is a kinesthetic receiving area in the raccoon cerebral cortex, in the medial central sulcus and the medial end of the lateral central sulcus. This area contains a somatotopic representation of the limb muscles, dominated by the distal forearm musculature.

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