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**Midline and Lateral Field Sound Localization in the
Ferret (Mustela putorius): Contribution of the Superior
Olivary Complex**

by

Gerard Leo Kavanagh, B.A., M.A.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Doctor of Philosophy

Department of Psychology

Carleton University

Ottawa, Ontario

January 3, 1990

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Midline and Lateral field sound localization in the ferret
(Mustela putorius): contribution of the superior olivary
complex

submitted by

Gerard Leo Kavanagh, BA., M.A.

in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

A handwritten signature in black ink, appearing to read "Bill Jones", written over a horizontal line.

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ABSTRACT

Although numerous studies have suggested that the superior olivary complex (SOC) is important for the integration of binaural cues for sound localization, there has been no direct behavioral confirmation that the SOC is essential. Because of technical difficulties associated with making lesions restricted to the SOC, behavioral studies to date have focused on the effects of surgical section or electrolytic lesions of the trapezoid body, the major source of afferent input to the SOC. Although results have shown that lesions of the trapezoid body can severely disrupt the ability to localize sound in space, interpretation of behavioral deficits is difficult. The TB, in addition to containing fibers which terminate in the SOC, also contains fibers which bypass the SOC and terminate in higher auditory centers. It is impossible, therefore, to know the extent to which nuclei within the SOC, as opposed to fibers of passage within the TB, are responsible for behavioral deficits reported in the existing literature. In the present study the effects of SOC lesions were investigated in sixteen adult male ferrets using the neurotoxin kainic acid which allows for selective destruction of cell bodies without damage to fibers of passage within the TB. Minimum audible angles (MAAs) for localization of a brief 45 msec noise burst were obtained on midline as well as within the left and right hemifields of auditory space before and after surgery. Results showed that complete unilateral lesions of the SOC disrupted sound localization throughout the horizontal plane. The most severe

impairments were consistently observed within the hemifield ipsilateral to the lesion. Less severe impairments were also observed within the hemifield contralateral to lesion and on midline. These results indicate that the SOC is essential for the maintenance of accurate localization of sound in space.

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INTRODUCTION

In vision and somesthesia there is a one to one correspondence between location of a stimulus in the sensory domain and site of activation on the receptor surface, the retina or the skin (Kandel and Schwartz, 1981). Thus in these modalities, the sensory epithelium contains an orderly representation of spatial information which can be relayed to higher centres within the central nervous system by a simple sorting of fibers. The representation of auditory space, in contrast, is complicated because the sensory epithelium codes not for space but for sound frequency. Regardless of stimulus location, a particular frequency activates the same point on the basilar membrane, and different frequencies activate different points. In audition the main cues for determination of sound location derive from a comparison of physical energy at the two ears (Lewis, 1983; Mills, 1972).

The first main cue for sound localization, interaural time difference (ITDs), refers to a disparity in the arrival time of sound at the ears. All sounds originating lateral to the median plane give rise to ITDs because the length of the sound path to the two ears is not equal. A sound presented in the right hemifield of auditory space will reach the right ear first because of the additional time required for the sound to travel around the head to the left ear. The opposite is true for sounds originating in the left hemifield (Mills, 1972; Woodworth, 1938). The magnitude of the ITD is dependent on stimulus location, head size, and to a lesser extent sound frequency.

ITDs are more pronounced at lateral azimuths, and in animals with large heads due to increased interaural travel time. In addition, ITDs associated with low frequencies are slightly larger than those for high frequencies due to differences in the diffraction pattern of the sound front around the head (Durlach and Colbourn, 1978). In man, sounds originating 15 and 90 degrees off midline give rise to ITDs around 200 and 800 microseconds compared to 125 and 350 microseconds at the same locations in the cat (Kuhn, 1977; Roth et al., 1980)

The ITD associated with a sound in space actually provides two separate time cues for localization. Transient time differences (TTDs), which refer to a disparity in sound onset or offset at the two ears, are present at all frequencies and are the only time cue available for localization of very brief stimuli such as clicks (Phillips and Brugge, 1985). For sustained stimuli an additional time cue is available in the form of interaural phase differences (IPDs), i.e., differences in the phase relation of a sound at the two ears (Mills, 1972). The usefulness of IPDs as a cue for sound localization relates to the fact that certain auditory neurons lock their discharge to a particular portion of each stimulus cycle, a property referred to as phase-locking (Goldberg and Brown, 1969). Phase-locking preserves temporal information that can then be processed by binaurally sensitive neurons in the SOC. At low frequencies where the waveform period exceeds the maximum ITD, each location in space generates a unique IPD and the probability of discharge in phase sensitive units can be used as

a cue for sound location. IPDs, however, are unreliable as a cue for localization at high frequencies because the maximum ITD can exceed the period of one stimulus cycle with only small changes in stimulus location. Consequently a given IPD can be associated with multiple locations (Mills, 1972). In addition at high frequencies the nervous system is unable to maintain the synchronous phase-locked activity required for analysis of IPDs (Johnson, 1980). In man, IPDs provide the major cue for localization of pure tones below about 1500 Hz (Mills, 1972).

The second major cue for sound localization, interaural intensity differences (IIDs), refers to an intensity disparity at the two ears. The head shadows or attenuates sounds originating from lateral azimuths such that intensity at the ear closest to the sound source exceeds that in the distant ear (Calford et al., 1986; Feddersen, 1957; Mills, 1972). The ability of the head to shadow the sound front, however, is dependent on frequency. At low frequencies where wavelength is large relative to head size, the head is essentially sound transparent and IIDs are small or absent. IIDs only become apparent at higher frequencies where wavelength is small relative to head size. The intensity disparity resulting from the shadowing effect of the head is made even more salient by the pinnae which act as directional amplifiers at high frequencies to increase intensity at the near ear (Calford and Pettigrew, 1984; Phillips et al., 1982). Like ITDs, the magnitude of the IID varies as a function of stimulus location,

becoming progressively larger at lateral azimuths. In man, maximum IIDs associated with sound originating 90 degrees off midline range from around 2-3 dB at 500 Hz to 20-30 dB at high frequencies (Fedderson et al., 1957).

Several lines of evidence suggest the superior olivary complex (SOC), a bilateral structure comprising a group of closely associated nuclei embedded within fibers of the trapezoid body in the ventral pons, is critical for the integration of binaural cues for sound localization. The most prominent nuclei within the SOC are the medial superior olive (MSO), the lateral superior olive (LSO), and the medial nucleus of the trapezoid body (MNTB). Surrounding these main nuclei are a number of smaller less distinct cell groups forming the lateral and ventral nuclei of the trapezoid body (LNTB and VNTB) and the periolivary nuclei (PN). Although available research suggests that all of these nuclei may be involved in various aspects of sound localization, the nuclei best understood in terms of binaural processing are the MSO and the LSO. As will be discussed below, anatomical and electrophysiological studies have shown that these two nuclei receive projections from both ears and are sensitive to ITDs and IIDs in the range used for sound localization. In addition, behavioral studies have shown that lesions of the trapezoid body, the major source of afferent input to the SOC, severely disrupt the ability to localize sound in space.

Anatomical studies suggest the MSO and the LSO are specialized to integrate binaural cues for sound localization.

The MSO, which in transverse section forms a distinct nucleus elongated dorsoventrally, contains neurons whose dendrites extend medially and laterally to form horizontal sheets or laminae (Kiss and Majorossy, 1983; Schwartz, 1977; Stotler, 1953). These dendritic laminae receive projections from the ipsilateral and contralateral anteroventral cochlear nucleus (AVCN) by way of medium diameter fibers in the trapezoid body. Fibers from the ipsilateral AVCN terminate predominantly on laterally oriented dendrites while those from the contralateral AVCN terminate on medially oriented dendrites (Goldberg and Brown, 1968; Harrison and Irving, 1966; Lindsey, 1975; Schwartz, 1980; Stotler, 1953; Strominger and Strominger, 1971; Warr, 1982). The segregation of afferents from ipsilateral and contralateral AVCN onto cells within the MSO makes the nucleus ideally suited to compare input from the two ears.

The LSO appears convoluted or S-shaped in transverse section and contains neurons with two-dimensional dendritic fields oriented perpendicular to the axis of nuclear curvature (Olo and Schwartz, 1979; Scheibel and Scheibel, 1974). This nucleus also receives projections from both ears, although the pattern of innervation is more complicated than for the MSO. Fibers from the the ipsilateral AVCN project directly to the LSO, while those from the contralateral AVCN and posteroventral cochlear nucleus (PVCN) reach the LSO via a disynaptic pathway involving the medial nucleus of the trapezoid body (MNTB). (Glendenning et al., 1985; Goldberg and

Brown, 1968; Harrison and Warr, 1962; Stotler, 1953; Strominger and Strominger, 1971; Warr, 1982). Relatively little is known about the distribution of synaptic terminals within the LSO, although there is some indication that ipsilateral AVCN efferents contact distal dendrites while those from the contralateral AVCN and PVCN, projecting to the LSO via the MNTB, contact cell bodies (Cant, 1984; Glendenning et al., 1985). These findings indicate that the LSO, through its association with the MNTB, is also ideally suited to compare input from the two ears.

Several lines of evidence suggest the MSO and the LSO are specialized for the integration of binaural cues associated with low and high frequency sound localization respectively. Comparative anatomical studies have shown that there is a strong correlation between the size of these nuclei in different species and the availability of ITDs and IIDs as a cue for localization (Harrison and Feldman, 1970; Irving and Harrison, 1967; Moore and Moore., 1971). In some primates, which have a large interaural separation and ample opportunity to use ITDs as a cue for localization, the MSO shows maximal development whereas the LSO is small or absent (Harrison and Feldman, 1970; Moore and Moore, 1971). Such species generally have good low frequency hearing, an evolutionary adaptation reflecting their dependence on ITDs as a cue for azimuthal localization (Heffner and Heffner, 1985). At the other extreme, the LSO is well developed while the MSO is small or absent in the hedgehog and some species of bat which

have a very small interaural separation (Irving and Harrison, 1967; Moore and Moore, 1971). These species generally have good high frequency hearing, an observation consistent with the idea that they depend primarily on IIDs for azimuthal localization (Heffner and Heffner, 1985). The majority of mammals, including those commonly used for auditory research such as the cat, dog and ferret, fall intermediate between these two extremes and have a well developed MSO and LSO (Irving and Harrison, 1967; Moore and Moore, 1971). Such species generally have a broad range of hearing, and depend on ITDs and IIDs for sound localization (Heffner and Heffner, 1985).

Although there has been no direct confirmation that the LSO is essential for comparison of IIDs, Masterton et al. (1975) have shown the MSO is important for the analysis of ITDs for low frequency sound localization. They compared sound localization ability in the cat, tree shrew, rat and hedgehog. All of these species have a large LSO, but the MSO shows varying degrees of development. The cat has a large MSO, the tree shrew a moderate sized MSO, and the rat a small MSO. As mentioned above, the hedgehog has no MSO at all. Stimuli were pure tones with a duration and rise time such that localization depended on IPDs at low frequencies and IIDs at high frequencies. Results showed a close correspondence between the ability to utilize IPDs and the size of the MSO. The cat, tree shrew and rat were all able to localize low frequency tones, although performance for the cat and tree

shrew was slightly better than that for the rat as would be expected on the basis of relative MSO size. In contrast, the hedgehog which lacks an MSO, was incapable of localizing pure tones in the low frequency range of its audiogram.

Physiological studies have shown that the MSO and LSO each contain an orderly representation of sound frequency. In the MSO, units with low characteristic frequencies (CFs), i.e., those which show maximal sensitivity to low frequency tones, are located dorsally while those with high CFs are located more ventrally within the nucleus (Guinan et al., 1972 a,b; Goldberg and Brown, 1968; Harnischfeger et al., 1985). The amount of tissue devoted to the representation of low frequencies, however, is disproportionately large suggesting the MSO is involved primarily in an integration of binaural cues for low frequency localization. In the cat, whose upper range of hearing extends beyond 60 kHz (Heffner and Heffner, 1985) and the dog, the majority of units within the MSO have CFs below 4 kHz and very units few have CFs greater than 10 kHz (Guinan et al., 1972 a,b; Goldberg and Brown, 1968). The disproportionate representation of low frequencies within the MSO is consistent with anatomical and physiological studies of the large spherical cell area, the region of the AVCN which projects to the MSO. Innervation to this area is restricted primarily to low and middle frequency auditory nerve fibers and the majority of neurons have CFs below 10 kHz (Bourk et al., 1981; Osen, 1970).

Within the LSO, neurons with low CFs are located in the lateral limb of the nucleus while those with high CFs are located in the medial limb (Boudreau and Tsuchitani, 1970; Guinan et al., 1972 a,b; Tsuchitani, 1977). In contrast to the MSO, however, there is a disproportionate representation of high frequencies within the LSO. Electrode penetrations into the nucleus have shown that the majority of units have CFs above 10 kHz and relatively few neurons show maximal sensitivity to sound frequencies below 4 kHz (Guinan et al., 1972 a,b). The differential distribution in favor of high frequencies suggests the LSO is involved primarily in the comparison of binaural cues for high frequency localization.

The vast majority of neurons within the MSO and LSO are binaurally sensitive, i.e., they respond to stimulation of either ear alone. In the MSO, the most common type of response encountered is excitatory/excitatory (EE) in which monaural stimulation of either ear produces an increase in discharge rate (Goldberg and Brown, 1968; Guinan et al., 1972 a,b; Inbody and Feng, 1981). Studies have shown that most EE cells are sensitive to IPDs important for low frequency sound localization (Goldberg and Brown, 1969). The mechanisms underlying phase sensitivity relate to the fact that EE cells show an excitatory phase-locked response to both ipsilateral and contralateral monaural stimulation. When the ears are stimulated binaurally with identical stimuli and IPDs are systematically manipulated, EE cells respond maximally at the interaural delay which brings the phase-locked points for the

two ears into coincidence. Although the data base is relatively small, there is some indication that the phase-locked response to ipsilateral monaural stimulation occurs earlier than that for contralateral stimulation (Goldberg and Brown, 1969). The most favorable delays for the majority of EE neurons, therefore, are those in which the contralateral ear leads, a finding consistent with the idea that EE cells use IPDs to code for contralateral azimuths.

Although the majority of binaurally sensitive neurons within the MSO are EE and sensitive to IPDs, a significant proportion show excitatory/inhibitory (EI) response profiles. They are excited by contralateral stimulation and inhibited by ipsilateral stimulation (Goldberg and Brown, 1968; Guinan et al., 1972; Inbody and Feng, 1981). Studies have shown that these EI neurons are sensitive to IIDs. The response to excitatory contralateral stimulation shows a progressive decline as intensity of the ipsilateral inhibitory stimulus is increased. When intensity at the ipsilateral ear equals or exceeds that at the contralateral ear, EI neurons generally show a complete suppression of neural activity (Goldberg and Brown, 1969; Inbody and Feng, 1981). Thus EI cells show a graded excitation over the range of IIDs corresponding to contralateral azimuths and total inhibition over the range of IIDs corresponding to ipsilateral azimuths. These results suggest that IID sensitive neurons within the MSO, like those sensitive to IPDs, code for contralateral azimuths. Studies of glucose metabolism also suggest the MSO codes for

contralateral space. In cats injected with 2-deoxyglucose and stimulated with a laterally placed low frequency sound source, dense label is seen in the MSO contralateral to the side of stimulation (Masterton et al., 1981).

In the LSO virtually all binaurally sensitive neurons are excited by stimulation of one ear, inhibited by stimulation of the other ear, and sensitive to IIDs. In contrast to the MSO, however, IID sensitive neurons within the LSO demonstrate inhibitory/excitatory (IE) response profiles. They are inhibited by contralateral monaural stimulation and excited by ipsilateral monaural stimulation (Boudreau and Tsuchitani, 1968; Caird and Klinke, 1983; Guinan et al., 1972 a,b; Tsuchitani, 1977). As in the MSO, binaural interaction studies have shown that the response to excitatory stimulation shows a progressive decline as intensity of the inhibitory stimulus is increased, with complete inhibition apparent when intensity at the inhibitory ear, in this case the contralateral ear, equals or exceeds that at the excitatory ear (Boudreau and Tsuchitani, 1968; Caird and Klinke, 1983; Tsuchitani and Boudreau, 1969). Thus IE neurons in the LSO process IIDs in the same way as EI neurons within the MSO. However, IID sensitive cells within the LSO respond over the range of IIDs corresponding to ipsilateral azimuths, whereas those within MSO respond over the range corresponding to contralateral azimuths. These results indicate that the LSO, unlike the MSO, codes primarily for ipsilateral azimuths.

Studies of binaural interaction have shown that EI and IE neurons, in addition to being sensitive to IIDs, are also sensitive to TTDs. In these neurons, sensitivity to TTDs is generally similar to IID sensitivity. Neurons respond maximally when the excitatory ear receives the earlier, as opposed to more intense stimulation, and minimally when the inhibitory ear is stimulated first (Caird and Klinke, 1983; Galambos et al., 1959; Hall, 1965; Harnischfeger et al., 1985). Thus EI cells in the MSO respond maximally when the contralateral ear is stimulated first, and IE neurons in the LSO respond maximally when the ipsilateral ear receives the earlier stimulation. These results suggest that TTDs, like IIDs and IPDs, are used to code for contralateral azimuths in the MSO and ipsilateral azimuths in the LSO.

Behavioral studies also suggest the MSO and the LSO are important for the integration of binaural cues for sound localization. Because of technical difficulties associated with making lesions restricted to the SOC, however, most investigators have examined the effects of trapezoid body lesions, the major source of binaural input to the SOC. Masterton et al. (1967) tested cats for their ability to discriminate small ITDs following surgical section or electrolytic lesions of the trapezoid body. Results showed that complete section of the trapezoid body produced a severe impairment in the ability to discriminate ITDs in the range used for sound localization. Whereas normal animals were able to discriminate ITDs as small as 50 microseconds,

animals with complete lesions of the trapezoid body were unable to perform above the level expected by chance, even with an interaural delay of 500 microseconds. Animals with subtotal lesions of the trapezoid body were able to discriminate large ITDs but thresholds for discrimination of smaller ITDs were elevated relative to normal.

Lesions of the trapezoid body have also been shown to disrupt the ability to localize sound in space. Casseday and Neff (1975) evaluated the effects of trapezoid body section using a midline 2-choice test which allows for determination of minimum audible angles (MAAs) around 0 degrees azimuth. Whereas preoperative MAAs were in the range of 5-10 degrees, cats with complete lesions of the trapezoid body were totally incapable of localizing brief sounds, even with an angular separation of 90 degrees. Impairments in midline localization subsequent to trapezoid body lesions were also reported by Moore et al. (1974) who found that performance for cats with complete lesions of the trapezoid body was similar to that observed in animals rendered monaural by cochlear destruction. In both of the above mentioned studies subtotal lesions of the trapezoid body had little or no effect on MAAs for midline localization. Jenkins and Masterton (1982) evaluated the effects of trapezoid body lesions using a more refined 7-choice procedure which allows for assessment of localization ability in the left and right hemifields of auditory space. In this study complete section of the trapezoid body

was shown to result in an incapacity for sound localization in both the left and right hemifields of auditory space.

Although the above behavioral studies suggest the MSO and the LSO are important for the integration of binaural cues, they do not provide direct confirmation that the SOC is essential for sound localization. It is quite possible that lesions restricted to the SOC would yield a pattern of behavioral deficits different from those observed following surgical section or electrolytic lesions of the trapezoid body. The trapezoid body, in addition to containing fibers which terminate in the SOC, also contains fibers which originate in the cochlear nuclei, bypass the SOC, and terminate in higher auditory centers such as the nuclei of the lateral lemniscus and the inferior colliculus (Warr, 1982). It is impossible, therefore, to know the extent to which nuclei within the SOC, as opposed to fibers of passage within the TB, are responsible for behavioral deficits reported in the existing literature.

The proposed research will examine the effects of kainic acid lesions of the SOC in the ferret on the ability to localize sound in space. Previous anatomical studies (Masterton et al., 1979) and pilot work conducted in our laboratory (Kavanagh and Kelly, 1986) have shown that microinjections of kainic acid into the SOC result in complete destruction of cell bodies, without damage to fibers of passage within the trapezoid body. Animals will be tested before and after surgery for their ability to localize brief sounds on midline as well as within the left and right hemifields of auditory space. This study,

therefore, will provide the first systematic investigation of the unique functional contribution of the SOC to sound localization.

METHODS

Subjects

The effects of kainic acid lesions of the superior olivary complex (SOC) on sound localization were examined in over 50 pigmented adult male ferrets (Mustela putorius) obtained from Marshall Research Animals, North Rose, New York. Because of the high mortality rate associated with brainstem lesions in carnivores, however, behavioral results are available for only 16 ferrets. Of these animals six received complete unilateral lesions of the left (F154, F74, F155, F77) or right (F76 and F129) SOC, four received partial unilateral lesions of the left (F102 and F81) or right (F83 and F82) SOC, and two (F75 and F84) received unilateral lesions which spared the SOC. One ferret (F79) received a complete bilateral lesion of the SOC, and three ferrets (F172, F210 and F125) received bilateral lesions which caused complete or near complete destruction of the SOC on one side and minimal damage on the other side. With the exception of F79 and F125, ferrets were tested preoperatively and postoperatively for their ability to localize on midline as well as within the left and right hemifields of auditory space. Animals were housed individually in stainless steel cages (61 X 61 X 76 cm.) and provided ad libitum food and water except during behavioral testing in which case they

received their daily water requirement in the test apparatus. The condition of the external ear canals was monitored by regular otoscopic examination, and the condition of the tympanic membranes and middle ears was determined by postmortem dissection.

Apparatus

Animals were trained and tested in a semicircular apparatus with a radius of 92 cm. The floor was constructed of 1.3 cm plywood. The sides and top were made of 1.3 cm square reinforced wire mesh. A platform (length, 37 cm; width, 10 cm; height, 2.5 cm) was located at the back of the apparatus and serve as a start area from which animals could initiate trials. The back third of the start area was covered with 3 mm copper plating, and a wire tunnel, 17 cm in diameter, was located over the center third. A center spout, 11 cm high, was located 9 cm in front of the start area at the center of the apparatus. Animals were able to initiate a trial by keeping their hind feet on the copper plate, stretching forward through the wire tunnel, and touching their nose to the center spout.

Loudspeakers were suspended around the outside perimeter of the apparatus at a height of 14 cm. In the midline test loudspeakers were located at -30 and +30 degrees azimuth initially and then moved closer together for testing at smaller angles of separation. Assessment in the left and right hemifields began with speakers separated by 60 degrees, centered around either -60 or +60 degrees azimuth,

respectively. As in the midline test, speakers were moved closer together for testing at smaller angles of separation.

Solenoid-operated water spouts were mounted in the wall of the apparatus 6 cm above the floor. In the midline test, spouts were located at -30 and +30 degrees azimuth. Spouts were located at -90 and -30 degrees for testing in the left hemifield and at +30 and +90 degrees for testing in the right hemifield. Contact between the water spout and a stainless steel plate (25 cm wide) located on the floor around the periphery of the apparatus provided the electrical circuit necessary for delivery of reinforcement.

The test apparatus was contained within a soundproof chamber (Eckel Industries) in a room separate from the experimenter and sound generating equipment. To reduce reflected sound, the walls and ceiling of the chamber were insulated with 5 cm fiberglass batting and draped with several layers of heavy burlap. A closed circuit television camera (Sony AVC 3200) mounted above the test apparatus was used to observe the animals' behavior during testing. Stimulus presentation, water delivery, and response tabulation was controlled by a microprocessor (Apple II) programmed in UCSD Pascal, and an interface designed by Carleton University's Science and Technology Center.

Sound Generation

Broad band noise was produced by a white noise generator (Grason-Stadler 455C), switched (Colbourn S84-04), amplified (Aiwa P30) and transduced by Philips loudspeakers

(ADO 160/T8). Loudspeakers were matched in intensity within plus and minus one dB for one-third octave frequency bands between 250 and 40,000 Hz. Stimulus duration was 45 msec and the intensity measured at the start area with a measuring amplifier (Bruel and Kjaer 2606) and a 0.5 in. microphone (Bruel and Kjaer 4133) was 85 dB (re 20 uPa). The predominant energy of the stimulus was between 800 Hz and 20,000 Hz.

Training

During training, which took place in two stages designed to shape animals to initiate trials from the center spout, speakers and response spouts were located at -30 and +30 degrees azimuth and the stimulus was a continuous train of 45 msec noise bursts presented at a rate of 2/sec. In the first stage of training water deprived ferrets were allowed to move freely in the apparatus while the stimulus was presented automatically from one of the two loudspeakers. Animals were required to contact the response spout below the active loudspeaker in order to obtain water reinforcement (0.3 ml). This stage of training served to familiarize animals with basic stimulus-response contingencies and continued for approximately 100 reinforcements.

In the second stage of training stimulus presentation was controlled by the experimenter and ferrets were shaped by successive approximation to enter the start area, initiate a stimulus presentation by contacting the center spout, and respond to the appropriate water spout. In the case of a

correct response, i.e., contact with the response spout below the active loudspeaker, water reinforcement was delivered immediately and the stimulus was discontinued. The position of the stimulus for the next trial was then determined randomly. In the case of an incorrect response the stimulus was discontinued and no reinforcement was delivered. On subsequent trials the stimulus was presented from the same location until a correct response was made. This "correction procedure" served to prevent animals from forming a position preference for one spout or the other. Testing began when an animal reliably initiated its own trials from the start area.

Midline and Hemifield tests

Tests of midline localization began with speakers separated by 60 degrees, centered around 0 degrees azimuth. Following this, speakers were moved closer together and animals were tested at successively smaller angles of separation (40, 20, 10, 6, and 0 degrees) provided performance remained above the level expected by chance. At 60 degrees separation, animals were tested first with noise bursts presented at a rate of 2/sec and then with single 45 msec noise bursts presented at the beginning of each trial. Tests at smaller angles of separation were conducted with single noise bursts only.

Testing in the left and right hemifields, began with speakers separated by 60 degrees, centered around either -60 or +60 degrees azimuth respectively. As in the midline test, animals were tested first with 2/sec noise bursts in order to

familiarize them with the location of response spouts and then with single noise bursts. Upon completion of testing at 60 degrees, animals were tested with single noise bursts at successively smaller angles of speaker separation.

In each of the three test situations performance was defined in terms of the percentage of correct responses obtained at each angle of speaker separation. Performance was based on trials that occurred immediately following a correct response, i.e., on trials in which the location of the stimulus was randomly assigned to one of the two speaker positions. Trials that occurred following an incorrect response, i.e., correction trials, were excluded because the stimulus position remained unchanged from the previous trial. Performance scores at 60 degrees separation were based on three successive blocks of 50 trials in which there is no evidence of improvement. At smaller angles performance was based on two successive blocks of 50 trials with no evidence of improvement. For each of the three test situations performance curves were determined from the percentage scores at each angle of speaker separation, and a minimum audible angle (MAA) at which animals obtained 75% correct was arrived at by extrapolation. In the event that animals were unable to attain 75% correct, performance was compared with the level expected by chance according to the binomial distribution ($P = 0.05$), which was 59.8% or 58% correct based on 100 and 150 trials respectively.

Surgery and Histology

In preparation for surgery, ferrets were food deprived 12 hours, anesthetized with pentobarbital sodium (35 mg/kg, i.p.) and administered atropine sulphate (0.05 mg/kg, s.c.). Animals were then placed in a head holder, a midline incision was made under aseptic conditions, and the scalp and temporal musculature were retracted to expose the skull. A small hole was drilled in the parietal bone and a glass micropipette with a tip diameter of 60 to 80 microns was inserted stereotaxically through the cerebellum until the tip was located just dorsal to the SOC. Stereotaxic coordinates (anterior 8 mm; lateral 2.5 mm; ventral 12 mm) were based on a flat skull preparation and referenced to the nuchal crest, since neither bregma nor lambda are clearly defined in the ferret. The pipette was filled with kainic acid dissolved in Locke's solution (1 mg/cc) and connected via plastic tubing (PE 10) to a 10 ul syringe (Hamilton 701). The tubing and syringe were filled with distilled water and separated from the kainic acid in the micropipette by a small air bubble. The Hamilton syringe was placed in a micropump (Razel 73769) and 1 ul kainic acid was injected over a five minute period. Movement of the air bubble interposed between the kainic acid and the distilled water was used to gauge the amount of kainic acid injected. The micropipette was left in the brain for fifteen minutes following the injection to allow for diffusion of the kainic acid. After removal of the micropipette the burr hole was packed with gelfoam moistened in saline and the temporal

musculature and scalp were sutured in place. Postoperative testing began following a recovery period of three to four weeks.

Upon completion of postoperative testing, brain damaged ferrets were given a lethal dose of pentobarbital sodium (100 mg/kg) and perfused through the ascending aorta with saline followed by 10% formalin. Brains were removed, embedded in gelatin or celloidin, and sectioned at 40 microns in the frontal plane. Alternate sets of tissue were stained with cresyl violet for cell bodies and protargol for fibers. In each case histological material was examined by two trained observers and the extent of degeneration within individual nuclei of the SOC was classified qualitatively as either complete (95-100% cell loss), severe (75-95% cell loss), moderate (45-75% cell loss), or mild (15-45% cell loss). Tissue in which cell loss was estimated to be less than 15% was considered normal. Following examination of the histological material, the extent of damage in each case was reconstructed and illustrated at 400 micron intervals on drawings of standard frontal sections through the SOC of a normal ferret brain. As mentioned earlier, the nuclei best understood in terms of binaural processing are the MSO and the LSO. Cases in which these nuclei were completely destroyed, therefore, were considered to be complete SOC lesions.

RESULTS

Ferret SOC

Photomicrographs in Fig. 1 illustrate a series of caudal to rostral frontal sections at 400 micron intervals through the SOC in a normal ferret. As in other mammals, the SOC in the ferret comprises three main nuclei, the lateral superior olive (LSO), the medial superior olive (MSO), and the medial nucleus of the trapezoid body (MNTB). The LSO appears circular in shape at the caudal and rostral extremes of the SOC (plates A and D, respectively) but takes on a characteristic S-shape at more intermediate levels (plates B and C). The MSO is clearly recognizable at all levels as a crescent shaped nucleus angled at about 45 degrees from dorsomedial to ventrolateral. The medial nucleus of the trapezoid body (MNTB), situated ventromedial to the MSO, is not as clearly defined as the other major nuclei due to extensive interdigitation of trapezoid body (TB) fiber fascicles between cell aggregates within the nucleus. Surrounding the main nuclei of the SOC are a number of smaller cell groups, the most prominent of which are the ventral nucleus of the trapezoid body (VNTB) situated ventromedial to the MNTB, and the lateral nucleus of the trapezoid body (LNTB) located on the ventral margin of the LSO. At the most rostral extent of the SOC (see Fig. 4) the MSO and MNTB are still apparent, but the LSO disappears and is replaced by a poorly defined cluster of neurons referred to as the transitional zone (TZ). More rostrally the transitional zone blends with the ventral nucleus of the lateral lemniscus

(VNLL), which in turn is replaced by the intermediate and dorsal nuclei of the lateral lemniscus (INLL and DNLL) at progressively more rostral levels through the auditory brainstem.

Kainic Acid Damage

Photomicrographs in Fig. 2 show the appearance of the SOC in F76 following a unilateral kainic acid lesion of the right SOC. As can be seen in plate B, injection of kainic acid resulted in complete destruction of all nuclei within the right SOC without any obvious damage to fibers within the trapezoid body. Examination of individual nuclei under high magnification revealed a complete absence of neurons (plate D). Although the SOC was completely destroyed on the right, there was no evidence of damage to the left SOC. All major nuclei on the left appeared normal under low magnification (plate A) and examination under high power revealed a normal complement of healthy neurons (plate C). Damage in this case is representative of that seen in other animals with complete lesions of the SOC.

Preservation of Fibers of Passage

It was important for this study to verify that kainic acid lesions of the SOC spare fibers of passage within the trapezoid body, since integrity of the trapezoid body is critical to the interpretation of any behavioral deficits. In order to determine the effect of kainic acid lesions of the SOC on fibers within the trapezoid body, histological material was processed using the fiber stain protargol. Fig. 3 shows

representative protargol stained frontal sections through the SOC of F76, the same case presented in Fig. 2. As can be seen in the low magnification photomicrographs illustrated in plates A and B, fibers of the trapezoid body course ventral to the LSO and MSO, and through the MNTB, both ipsilateral and contralateral to the lesion. Plates C and D show high magnification photomicrographs through the MNTB ipsilateral and contralateral to the lesion. Note the presence of fiber fascicles travelling through the MNTB on the left and on the right side of the brain, despite the fact that the MNTB was completely destroyed on the right. These results are similar to those observed in protargol material from other ferrets and indicate that kainic acid does not cause any gross disruption of fibers of passage travelling within the trapezoid body.

General Observations

Before describing anatomical and behavioral results for individual cases, it is important to mention that small injections of kainic acid into the SOC did not result in damage to structures remote from the lesion. Although the rostral extent of the facial nucleus was degenerated in some cases and scattered degeneration was noted throughout the brainstem reticular formation in others, systematic examination of remote brain regions, including those particularly vulnerable to the effects of kainic acid such as the amygdala and hippocampus, showed no evidence of damage.

It is also important to mention that none of the animals reported in this study, with the exception of F79 (see

discussion of behavioral results) suffered any sort of generalized motor or intellectual impairment that could account for the observed behavioral deficits. All animals maintained familiarity with the test procedure following surgery and were able to initiate trials from the center spout and make appropriate behavioral responses under conditions where localization was possible. When tested with 2/sec noise bursts performance in every case was in excess of 90% correct on midline and within both the left and right hemifields. Behavioral results reported below reflect impairments during critical tests of sound localization with single 45 msec noise bursts.

Control Lesions

Two ferrets (F75 and F84) received unilateral lesions which caused little or no damage to the SOC. In F75, the micropipette terminated caudal to the SOC on the left side resulting in severe degeneration throughout the anterior extent of the facial nucleus. Damage, however, did not extend rostrally and there was no evidence of degeneration in any of the nuclei within the SOC. In F84 the micropipette terminated dorsal to the SOC on the right side. In this case there was some indication of very mild degeneration confined to the dorsal aspect of the MSO caudally. Damage to the MSO, however, was very minimal and the remainder of the SOC was completely unaffected.

Preoperative and postoperative performance curves for F75 and F84 are shown in Fig. 4. As can be seen, preoperative

and postoperative psychophysical curves for midline and lateral field sound localization were very similar in both cases. Postoperative MAAs for F84 on midline and within the left and right hemifields were within 3 degrees of those obtained preoperatively. Similar results were obtained for F75 within the lateral fields, although this animal showed a slight improvement on midline postoperatively, where the MAA was 9 degrees compared to 18.5 degrees preoperatively.

Because lesions produced little or no damage to the SOC, serve as behavioral controls for 1) the effects of repeated testing, and 2) the effects of surgical intervention independent of damage to the SOC. As can be seen in Fig. 4, neither animal showed any improvement in performance with postoperative testing, a finding consistent with previous studies of the effects of repeated testing in normal ferrets (Kavanagh and Kelly, 1986). In addition these results show that lesions which spare the SOC fail to disrupt the ability to localize sound in space indicating that the surgical approach itself had no detrimental effect on behavior.

Complete Left SOC Lesions:

As can be seen in the anatomical reconstructions shown in Fig. 5, four ferrets (F154, 174, 155, and F77) received, what for the purpose of the present study can be considered complete unilateral lesions of the left SOC. In each of these cases the MSO and the LSO were completely degenerated throughout the caudal to rostral extent of the SOC. The MNTB, LNTB and VNTB were also completely degenerated in two cases (F74 and F77).

In the remaining ferrets (F154 and 155) some sparing was observed in ventral tip of the MNTB, and damage to the LNTB and VNTB was classified mainly as severe. In all four cases the TZ and caudal aspect of the VNLL were also completely degenerated. At intermediate levels the VNLL showed varying degrees of degeneration, ranging from moderate to complete. In no case was there any evidence of degeneration within the most rostral extent of the VNLL or within the INLL.

Preoperative and postoperative midline and lateral field performance for F154, F74, F155 and F77 is shown in Fig. 6. As can be seen individual animals showed varying degrees of impairment on midline following surgery. The most severe impairment in midline localization was noted in F154. Preoperatively, this animal performed in excess of 85% correct at separation angles of 60 through 10 degrees and had a MAA of 9 degrees. Postoperatively, however, this animal obtained only 61% correct at 60 degrees separation and performance at 40 degrees was not above the level expected by chance. Less severe impairments in midline localization were noted in F74 and F155. These animals maintained relatively high performance levels at large angles of speaker separation postoperatively, but performance scores at smaller angles were inferior to those obtained preoperatively. MAAs for F74 and F155 were 25 and 30 degrees postoperatively, compared to 14 and 16 degrees preoperatively. In contrast to the above animals, F77 showed no obvious impairment in midline

localization. following surgery Preoperative and postoperative MAAs in this case were within 3 degrees of one another.

As was the case with midline localization, complete unilateral lesions of the left SOC also produced varying degrees of impairment within the hemifield contralateral to the lesion. Deficits were most severe in F154 and F74. Preoperatively, these ferrets performed at levels in excess of 90% correct at large angles of speaker separation and had MAAs of 16 and 19.5 degrees respectively. Postoperatively, F154 obtained only 64% correct at 60 degrees separation and F74 obtained only 59% correct. Neither animal performed above the level expected by chance at 40 degrees separation. F155 also performed poorly in the right hemifield following surgery. Performance scores at 60 and 40 degrees separation were 61% and 63% correct respectively. The severe postoperative deficit in this case, however, must be interpreted with caution as preoperative performance was very poor. In contrast to the above animals, F77 showed little or no sign of a deficit within the right hemifield postoperatively. Although no preoperative right hemifield data was collected on this animal, postoperative performance was not unlike that seen in normal animals. Performance scores at 60 and 40 degrees separation were in excess of 90% correct and the MAA was estimated to be 29 degrees.

Severe impairments in the ability to localize brief noise bursts were consistently noted in the hemifield ipsilateral to the lesion. As can be seen in Fig. 6, F154, F74, F155 and F77

were all capable of high performance levels in the left hemifield preoperatively, with MAAs ranging between 18 and 32 degrees.. Following surgery, however, performance levels were very low, even at large angles of speaker separation, and it was impossible to obtain MAAs in any of these cases. F154 did not respond above the level expected by chance with speakers separated by 60 degrees. F74 and F77 obtained 70% and 62% correct respectively at 60 degrees separation, but neither animal performed above chance when the separation angle was reduced to 40 degrees. F155 obtained 69% and 65% at separation angles of 60 and 40 degrees respectively, but did not perform above chance at 20 degrees separation.

Partial Left SOC Lesions

Two ferrets (F102, and F81) received partial lesions of the left SOC. As can be seen in Fig. 7, damage to the main olivary nuclei was most extensive in F102. In this case the MSO and the LSO were completely degenerated at caudal and intermediate levels. More rostrally, scattered neurons were noted in both nuclei and degeneration was classified mainly as severe. The MNTB, LNTB and VNTB were also completely degenerated caudally, but showed varying degrees of sparing rostrally. No damage was apparent within the TZ, VNLL or INLL in this case. In F81 the MSO was completely degenerated, but significant sparing was apparent throughout the LSO at caudal and intermediate levels. The LNTB was also completely degenerated in this case, with some sparing evident in the ventral tip of the MNTB and throughout the VNTB caudally.

More rostrally, the VNTB and the MNTB were completely degenerated as was the TZ. Damage to the nuclei of the lateral lemniscus was confined to the most caudal extent of the VNLL.

Preoperative and postoperative midline and lateral field performance for F102 and F81 is shown in Fig. 8. As can be seen, MAAs for midline sound localization were elevated in both cases postoperatively, but deficits were not severe and animals were capable of relatively high performance levels at large angles of speaker separation. F102 had a MAA of 16.5 degrees on midline preoperatively, compared to 27 degrees postoperatively. F81 had a preoperative MAA of 6 degrees, compared to 17.5 degrees following surgery.

Both animals also showed impairments in the hemifield contralateral to the lesion, with the most severe deficit apparent in F102. This animal obtained 98% and 92% correct at separation angles of 60 and 40 degrees preoperatively, and had a MAA of 25 degrees. Postoperatively, however, F102 obtained only 71% correct with speakers separated by 60 degrees, with performance falling below chance at 40 degrees. F81 did somewhat better than F102 following surgery, although performance was clearly inferior to that obtained preoperatively. This animal had a postoperative MAA of 42.5 degrees in the right hemifield, compared to 29 degrees preoperatively.

F102 and F81 also showed impairments in sound localization within the hemifield ipsilateral to the lesion. F102 maintained high performance levels at large angles of

speaker separation preoperatively and had a MAA of 26 degrees. Postoperatively, F102 obtained only 71% correct with speakers separated by 60 degrees, and did not perform above chance at 40 degrees separation. F81 in contrast, did surprisingly well in the left hemifield, although performance was still inferior to that obtained preoperatively. Postoperatively, this animal obtained 93% correct at 60 degrees separation and continued to respond above the level expected by chance at separation angles of 40 and 20 degrees. The lesion in this animal, however, spared a significant amount of tissue within the LSO and that may have been a contributing factor in the absence of a severe ipsilateral field deficit. The MAA in this case was 40 degrees following surgery, compared to 26 degrees preoperatively.

Complete Right SOC Lesions

Two ferret (F76 and F129) received complete unilateral lesions of the right SOC. As can be seen in Fig. 9, damage in these cases, with the exception of being on the right side of the brainstem, was similar to that found in ferrets with complete lesions of the left SOC. In both ferrets the MSO and LSO were completely destroyed throughout the caudal to rostral extent of the SOC. The MNTB, LNTB, VNTB and TZ were also completely degenerated in F76, and within F129 with exception of some sparing caudally within the VNTB and the ventrolateral aspect of the MNTB. In F76 the VNLL, with the exception of the most rostral extent, was completely degenerated, and severe degeneration was noted throughout the

INLL caudally. In F129 the caudal aspect of the VNLL was also completely degenerated but there was little evidence of damage at more rostral levels.

Preoperative and postoperative midline and lateral field performance for F76 and F129 is shown in Fig. 10. As can be seen, both animals were impaired in their ability to localize sound on midline following surgery. F76 had a postoperative MAA of 46.5 degrees, compared to 17 degrees preoperatively. The deficit in midline sound localization for F129 was slightly less severe. This animal was capable of high performance levels at large angles of speaker separation postoperatively but had difficulty at smaller angles. The postoperative MAA in this case was 32 degrees, compared to 9.5 degrees preoperatively.

Impairments in sound localization were also noted within the hemifield contralateral to the lesion. In the left hemifield F76 obtained in excess of 90% correct at separations of 60 and 40 degrees preoperatively, and had a MAA of 19 degrees. Postoperatively, F76 obtained only 76% and 60% correct at the same angular separations, and had a MAA of 58 degrees. F129 had a preoperative MAA of 41 degrees in the left hemifield, somewhat larger than that found in other normal animals. Postoperative performance, however, was still clearly inferior to that observed preoperatively. At the largest angle of speaker separation F129 obtained only 73% correct and performance at 40 degrees separation was not above the level expected by chance.

Both F76 and F129, like animals with complete lesions of the left SOC, were severely impaired in their ability to localize sound within the hemifield ipsilateral to the lesion. F76 was capable of very high performance levels within the right hemifield preoperatively, even at small angles of speaker separation, and had a MAA of only 16.5 degrees. Postoperatively, however, this animal was totally incapable of sound localization. Performance at 60 degrees separation was not above the level expected by chance. F129, was capable of high performance levels at 60 degrees separation following surgery, but performance at smaller angles was clearly inferior to that obtained preoperatively. The postoperative MAA in this case was 43 degrees, compared to 16 degrees preoperatively.

Partial Right SOC Lesions

Two ferrets (F83 and F82), received partial lesions of the right SOC (see Fig. 11). In F83 the MSO and LSO showed varying degrees of degeneration at caudal and intermediate levels, ranging from mild to complete, but both nuclei appeared normal more rostrally. Damage to the nuclei of the trapezoid body was likewise confined to caudal and intermediate levels of the SOC, and there was no evidence of degeneration within the TZ or within the nuclei of the lateral lemniscus in this case. In F82 the MSO was completely degenerated with the exception of a few scattered cells located ventrally at the caudal extreme of the nucleus. The medial limb of the LSO was also completely degenerated, but the remainder of the nucleus

appeared normal. Within the MNTB some sparing was apparent throughout the nucleus caudally and within the ventrolateral aspect at intermediate levels. Damage to the VNTB was classified as severe at all levels, whereas the LNTB appeared mainly normal. The TZ and the VNLL were completely degenerated in this case, as was the caudal aspect of the INLL.

Midline and lateral field performance for F83 and F82 is shown in Fig. 12. As can be seen, both cases showed impairments in midline sound localization following surgery. The deficit in F83, however, was not severe. Postoperative performance at 60 and 40 degrees separation was virtually identical to that obtained preoperatively. At smaller angles performance scores were reduced relative to those obtained preoperatively, but were still well above the level expected by chance. The postoperative MAA in this case was 13.5 degrees, compared to 6.5 degrees preoperatively. F82 had a more severe deficit in midline localization. Performance scores, even at large angles of speaker separation, were reduced substantially relative to those obtained preoperatively. Preoperative and postoperative MAAs in this case were 17.5 and 30 degrees respectively.

Impairments in sound localization were also found within the hemifield contralateral to the lesion. Although the left hemifield MAA for F83 was elevated only 5.5 degrees following surgery, postoperative performance scores were generally lower at all angles of speaker separation. F83 obtained 99%, 94% and 88% correct at separations of 60, 40

and 20 degrees preoperatively, compared to 87%, 78%, and 76% correct at the same angles postoperatively. F82 showed a slightly more severe deficit within the left hemifield postoperatively. Preoperatively this animal obtained 97%, 88% and 80% correct at separations of 60, 40 and 20 degrees respectively. Postoperatively, however, performance at 60 and 40 degrees separation was reduced relative to that obtained preoperatively, and performance at 20 degrees separation was not above the level expected by chance. The MAA in this case was 36 degrees postoperatively, compared to 17.5 degrees preoperatively.

More severe deficits were apparent within the hemifield ipsilateral to the lesion, particularly in the case of F83. Preoperatively, this animal was capable of relatively high performance levels at large angles of speaker separation, and had a MAA of 27 degrees. Postoperatively, however, it was impossible to obtain a MAA. F83 obtained only 61% correct with speakers separated by 60 degrees, and performance at 40 degrees separation was not above the level expected by chance. F82 showed a less severe deficit within the right hemifield. This animal was capable of accurate localization at 60 degrees separation following surgery, but performance scores at smaller angles of speaker separation were reduced relative to those obtained preoperatively. Preoperative and postoperative MAAs in this case were 26.5 and 48.5 degrees respectively.

Complete Bilateral SOC Lesions

As can be seen in Fig. 13, one animal (F79) received a complete bilateral lesions of the SOC. In this case the MSO and LSO were completely degenerated throughout the entire caudal to rostral extent of the SOC. The nuclei of the trapezoid body and the TZ were also completely degenerated with the exception of the ventrolateral aspect of the MNTB which showed some sparing on both the left and the right. Damage to the nuclei of the lateral lemniscus was confined to the caudal aspect of the VNLL on the left. On the right the VNLL was completely degenerated with the exception of the most rostral tip which showed severe degeneration

Preoperatively, this animal was capable of accurate localization on midline and within both lateral fields. Preoperative MAAs were 10, 14.5 and 15.5 degrees on midline and within the left and right hemifields respectively. This animal, however, was very difficult to evaluate postoperatively. When tested on midline with 2/s noise bursts, F79 obtained only 52% correct with speakers separated by 60 degrees, a performance score not above the level expected by chance. Unfortunately, this estimate was based on only 38 trials, and it is not know if performance with 2/s noise bursts would have improved with repeated testing, or if the animal would have showed any ability during critical tests of sound localization with single noise bursts. Repeated attempts to evaluate performance over period of several months proved futile and a decision was made after much

deliberation to terminate testing and sacrifice the animal for histological analysis.

Partial Bilateral SOC Lesions

Three ferrets (F172, F125 and F210) received bilateral lesions which caused complete or near complete destruction of the SOC on one side of brain but only minimal damage to the SCC on the other side. In F172 the left SOC was virtually destroyed, but the entire MSO and a significant portion of the LSO was spared on the right. F210 and F125, in contrast, had extensive lesions of the right SOC with only minimal damage on the left side.. Because of differences in the location of brain damage in these cases and the similarity to animals with complete unilateral lesions of the left and right SOC respectively, the results for F172 will be discussed independent of those for F125 and F210.

The extent of damage to the SOC in F172 is shown in Fig. 14. As can be seen the MSO and LSO were completely degenerated on the left side except for the most rostral tip of the MSO which showed severe degeneration. The LNTB was also completely degenerated on the left but the MNTB and the VNTB appeared normal except for some moderate degeneration caudally. The TZ was severely degenerated, but there was no indication of damage to the nuclei of the lateral lemniscus. On the right the LSO was completely degenerated at the caudal and rostral extremes of the SOC, but significant sparing was observed throughout medial limb of the nucleus at intermediate levels. There was no evidence of degeneration

within the MSO. The LNTB was completely degenerated on the right but MNTB and VNTB appeared normal at all levels. The TZ also appeared normal as did the nuclei of the lateral lemniscus.

Midline and lateral field performance for F172 is shown in Fig. 15. As can be seen this animal showed little evidence of a deficit in midline sound localization following surgery. F172 was capable of high performance levels at separations of 60 through 20 degrees, and had a postoperative MAA of 17.5 degrees, compared to 15 degrees preoperatively.

F172 also showed a slight impairment in sound localization within the right hemifield, the hemifield contralateral to the side in which brain damage was most extensive. Postoperative performance scores at 60 and 40 degrees separation, although still well above the level expected by chance, were reduced relative to those obtained preoperatively. The postoperative MAA in the right hemifield was 47.5 degrees, compared to 33.5 degrees before surgery.

A more severe deficit in sound localization was apparent within the left hemifield following surgery. Preoperatively, F172 obtained 94% and 84% correct at separations of 60 and 40 degrees respectively, and had a MAA of 28.5 degrees. Postoperatively, however, it was impossible to determine a MAA. F172 obtained only 73% correct with speakers separated by 60 degrees and performance at 40 degrees separation was not above the level expected by chance.

Anatomical reconstructions showing the extent of brain damage in F210 and F125 are shown in Fig. 16. In F210 the MSO was completely degenerated on the right side but some sparing was observed throughout the LSO rostrally and within the lateral limb of the nucleus at intermediate levels. The nuclei of the trapezoid body were completely degenerated on the right, with the exception of the LNTB which showed some sparing rostrally. Severe degeneration was noted throughout the TZ, but the nuclei of the lateral lemniscus showed little or no evidence of degeneration. On the left the pipette terminated very rostrally within the SOC and the MSO and the LSO appeared completely normal except for some moderate degeneration within the most rostral extent of the MSO. The LNTB and VNTB also appeared completely normal on the left, as did the MNTB, with the exception of some partial degeneration rostrally. Moderate degeneration was observed throughout the TZ, but damage to the nuclei of the lateral lemniscus was very extensive. The VNLL was completely degenerated as was the caudal aspect of the INLL.

In F125, the MSO and the LSO were completely degenerated on the right side. The MNTB and the LNTB were also completely degenerated on the right with the exception of some sparing within the MNTB rostrally. Damage to the VNTB was classified as severe at all levels through the SOC. The TZ was completely degenerated as was the caudal aspect of the VNLL. More rostrally the VNLL appeared normal. On the left MSO and LSO were completely degenerated caudally, but

appeared mainly normal at intermediate and rostral levels through the SOC. The MNTB and VNTB likewise showed severe degeneration caudally but appeared normal rostrally. No degeneration was apparent within the TZ or within the nuclei of the lateral lemniscus on the left.

Midline and lateral field performance for F210 and F125 is shown in Fig. 17. As can be seen both animals were still capable of accurate localization on midline following surgery. The postoperative midline performance curve for F210 was very similar to that obtained preoperatively with the exception of a slight reduction in performance levels at small angles of speaker separation. The MAA in this case was 18 degrees preoperatively, compared to 24.5 degrees postoperatively. F125 was not tested preoperatively but it is clear from his postoperative performance curve that midline localization was still possible. The animal obtained in excess of 90% correct at separations of 60 through 20 degrees following surgery and had a MAA of only 13.5 degrees.

Both animals showed an impairment in the ability to localize single noise bursts in the left hemifield, the hemifield contralateral to the side in which damage to the SOC was most extensive. Deficits, however, were not severe. Postoperative performance scores for F210 were generally inferior to those obtained preoperatively, but the animal was still capable of relatively high performance levels at separations of 60 and 40 degrees, and continued to respond above the level expected by chance at 20 degrees separation.

MAAs in the left hemifield, obtained preoperatively and postoperatively, were 36.5 and 49 degrees respectively. Although F125 was not tested preoperatively, postoperative performance scores within the left hemifield were generally lower than those obtained in normal animals. The animal obtained 72% and 84% correct at separations of 60 and 40 degrees, with performance at smaller angles falling below the level expected by chance. The postoperative MAA in this case was 34 degrees.

Both F210 and F125 were severely impaired in their ability to localize single noise bursts in the right hemifield, the hemifield ipsilateral to the side in which damage to the SOC was most extensive. Preoperatively, F210 was capable of high performance levels at separations of 60 and 40 degrees, and had a MAA of 35.5 degrees. Postoperatively, however, this animal was totally incapable of localizing single noise bursts. Performance was not above the level expected by chance, even with speakers separated by 60 degrees. F125 also showed a severe impairment in the ability to localize single noise bursts within the right hemifield following surgery. Performance scores, even at large angles of speaker separation, were only marginally above the level expected by chance.

Summary of Behavioral Results

Results of the present study indicate that complete unilateral lesions of the SOC disrupt the ability to localize sound throughout the horizontal plane. Severe deficits were

consistently observed within the hemifield ipsilateral to the lesion. Of six ferrets (F154, F74, F155, F77, F76 and F129) with complete unilateral lesions, two (F154 and F76) did not perform above the level expected by chance with speakers separated by 60 degrees. The remaining four performed marginally above chance at the larger angles of speaker separation, but postoperative performance was grossly inferior to that obtained preoperatively. In only one case (F129) was it possible to obtain a MAA in the hemifield ipsilateral to the lesion following surgery.

Animals with partial lesions of the left (F102 and F81) or right SOC (F83 and F82) also showed impairments in the ability to localize within the hemifield ipsilateral to the lesion. Postoperative performance in F102 and F76 was similar to that observed in animals with complete unilateral lesions. Less severe deficits were seen in F81 and F82, although in both cases MAAs were elevated substantially above preoperative estimates. Animals with bilateral lesions which caused complete or near complete destruction of the SOC on one side but only minimal damage on the other side likewise suffered a severe impairment in the ability to localize single noise bursts. Deficits in these cases, consistent with those observed in animals with complete or partial unilateral lesions of the SOC, were most severe in the hemifield ipsilateral to side in which damage to the SOC was extensive.

Impairments in sound localization were also observed within the contralateral hemifield following complete

unilateral lesions of the SOC. Of six ferrets with complete lesions, five (F154, F74, F155, F76 and F129) showed severe impairments. Postoperative performance in these cases was reduced drastically relative to that obtained preoperatively. Three of the four animals with partial unilateral lesions of the SOC (F102, F81, and F82) also suffered relatively severe impairments in the contralateral hemifield, similar to those observed ipsilaterally.

The above mentioned cases indicate that unilateral lesions of the SOC can disrupt sound localization equally in both the hemifield ipsilateral and contralateral to the lesion. Results from other animals, however, suggest that performance in the ipsilateral hemifield is particularly vulnerable. One ferret (F77) which had a complete lesion of the left SOC, although virtually incapable of sound localization ipsilateral to the lesion, obtained in excess of 90% correct at separations of 60 and 40 degrees in the contralateral hemifield, and had a MAA of only 29 degrees. Another animal (F83) with a partial lesion of the right SOC, also suffered a much less severe deficit within the contralateral hemifield, despite the fact that localization ipsilateral to the lesion was impossible. Less severe deficits were likewise seen in animals with complete or near complete destruction of the SOC on one side and minimal damage on the other side. These cases (F172, F210 and F125) all showed impairments in the ability to localize brief sounds contralateral to the side in

which damage to the SOC was most extensive, but deficits were not severe.

Impairments in midline sound localization were also noted following unilateral lesions of the SOC. Deficits, however, were generally less severe than those observed within the lateral fields. Of six ferrets with complete unilateral lesions, only one (F154) showed a severe deficit following surgery. This animal had a preoperative MAA of 9 degrees, but postoperative performance at 60 degrees separation was only marginally above the level expected by chance. The remaining animals with complete unilateral lesions of the SOC (F74, F155, F77, F76 and F129) were all capable of relatively high performance levels at the larger angles of speaker separation, but performance at smaller angles was reduced relative to that obtained preoperatively. Postoperative MAAs in these cases were elevated, on average, 16 degrees above preoperative estimates. Similar results were obtained for ferrets with partial unilateral lesions of the left (F102 and F81) or right (F83 and F82) SOC. Postoperative MAAs in these cases were elevated 7-12.5 degrees above preoperative estimates, but all animals were capable of localization at the larger angles of speaker separation. Animals with complete or near complete destruction of the SOC on one side and minimal damage on the other likewise suffered minimal impairments in midline sound localization. Preoperative and postoperative performance curves for F172 and F210 were very similar and MAAs were elevated only 2.5

and 6.5 degrees respectively. F125, was not tested preoperatively, but postoperative midline performance scores were very high at separations of 60 through 20 degrees and the MAA was only 13.5 degrees.

DISCUSSION

SOC is Important for Sound Localization

Several lines of evidence suggest that nuclei within the superior olivary complex (SOC), specifically the medial superior olive (MSO) and the lateral superior olive (LSO) are specialized for the integration of interaural time and interaural intensity differences, ITDs and IIDs, important for sound localization. Anatomical studies have shown that there is a convergence of input from the two ears in each of these nuclei, a critical prerequisite for the comparison of interaural disparities in time and intensity (Glendenning et al., 1985; Goldberg and Brown, 1968; Harrison and Irving, 1966; Harrison and Warr, 1962; Lindsey, 1975; Schwartz, 1980; Stotler, 1953; Stominger and Strominger, 1971; Warr, 1982). Electrophysiological studies have shown that the majority of units within the MSO and the LSO respond to monaural stimulation of either ear alone, and are sensitive to small ITDs and IIDs in the range used for sound localization (Boudreau and Tsuchitani, 1968; Caird and Klinke, 1983; Galambos et al., 1959; Goldberg and Brown, 1968, 1969; Guinan et al., 1972a,b; Hall, 1965; Harnischfeger et al., 1985; Inbody and Feng, 1981; Tsuchitani, 1977; Tsuchitani and Boudreau, 1969). Also,

comparative studies have shown that there is a strong correlation between the size of the MSO and LSO in different species and the availability of ITDs and IIDs as a cue for sound localization (Harrison and Feldman, 1970; Heffner and Heffner, 1985; Irving and Harrison, 1967; Masterton et al., 1975; Moore and Moore, 1971).

Although the above studies suggest the MSO and the LSO are important for the integration of binaural cues, there has been no direct behavioral confirmation that the SOC is essential for sound localization. Because of technical difficulties associated with making lesions restricted to the SOC, behavioral studies have focused on the effects of surgical section or electrolytic lesions of the trapezoid body, the major source of afferent input to the SOC (Casseday and Neff, 1975; Jenkins and Masterton, 1982; Masterton et al., 1967; Moore et al., 1974). Although results have shown that complete lesions of the trapezoid body can result in an incapacity for sound localization, interpretation of behavioral deficits is difficult or impossible. The trapezoid body, in addition to containing fibers which terminate in the SOC, also contains fibers which originate in the cochlear nuclei, bypass the SOC and terminate in higher auditory centers. It is impossible, therefore, to know the extent to which the SOC, as opposed to fibers of passage, are responsible for behavioral deficits reported to date.

Results of the present study indicate that the SOC is indeed important for sound localization. In every case destruction of the SOC with kainic acid, without obvious

damage to fibers of passage within the trapezoid body, produced severe impairments in the ability to localize sound in space. With complete unilateral lesions, severe impairments verging on a complete incapacity for sound localization were consistently observed in the hemifield ipsilateral to the lesion. Impairments were also seen within the hemifield contralateral to the lesion and on midline, indicating that unilateral SOC lesions disrupt the ability to localize sound throughout the horizontal plane.

The present results are inconclusive as to the effects of complete bilateral lesions of the SOC. Although attempts were made in a number of ferrets, the SOC was completely destroyed on both sides in only one case (F79). This animal, however, was very difficult to evaluate postoperatively and it is not clear whether the apparent inability to localize sound was attributable to some sort of generalized performance deficit. The possibility that some ability for sound localization remains following complete bilateral lesions of the SOC, therefore, cannot be ruled out.

Comparison with Lesions at Higher Levels: Acoustic Chiasm

Glendenning and Masterton (1983) and Glendenning et al. (1985) have suggested that the superior olivary complex and trapezoid body function as an acoustic chiasm similar in many respects to the optic chiasm in the visual system. Anatomically the auditory lower brain stem consists of several decussating pathways. The trapezoid body contains a

large number of fibers that originate in the cochlear nucleus, project across the midline and synapse in the contralateral auditory midbrain. The MSO receives fibers from both ipsilateral and contralateral cochlear nuclei and projects to midbrain structures on the same side of the brain. The LSO receives projections from the ipsilateral cochlear nuclei and projects to the auditory midbrain on both sides of the brain. Thus, the auditory system like the visual system is partially decussated.

Behavioral evidence indicates that the auditory system is functionally contralateral above the level of the superior olive (Jenkins and Masterton, 1982). In the cat, lesions at different levels of the auditory pathway produce different patterns of behavioral deficits. Unilateral damage of both forebrain and midbrain auditory structures result in impairments in sound localization in the opposite sound field whereas section of the trapezoid body produces either bilateral or ipsilateral deficits.

Results of the present study provide the opportunity for further direct comparison of the effects of unilateral lesions at different levels of the auditory pathway. We have previously examined the effects of unilateral lesions of the auditory cortex and the inferior colliculus in the ferret on midline and lateral field sound localization (Kavanagh and Kelly, 1987, 1988, 1989). Comparison of the present data with results of these studies is particularly instructive since

testing was conducted in the same apparatus and under identical stimulus conditions.

Previous studies of the effects of auditory cortical lesions in the ferret have shown that unilateral lesions of the primary and secondary auditory areas, or indeed unilateral lesions restricted to the primary auditory cortex (A1) alone, result in a complete incapacity to localize brief sounds within the hemifield contralateral to the lesion (Kavanagh and Kelly, 1987, 1988). In contrast, ferrets showed no impairment in the ability to localize brief sounds on midline or within the hemifield ipsilateral to the lesion. Minimum audible angles (MAAs) before and after surgery were virtually identical. These results suggest that the representation of auditory space is exclusively contralateral at the level of auditory cortex.

Large lesions of the inferior colliculus in the ferret also result in a complete inability to localize brief sounds in the hemifield contralateral to the lesion (Kavanagh and Kelly, 1989). In this study ferrets were incapable of responding above the level expected by chance in the contralateral field, even with speakers separated by 60 degrees. In contrast to cortical lesions, however, minimum audible angles were also elevated in the hemifield ipsilateral to the lesion and on midline. Elevations in these locations, however, were not large and all animals were capable of maintaining high performance levels at the larger angles of speaker separation. These results suggest that the representation of auditory

space at the level of midbrain is primarily, but not exclusively, contralateral.

Results of the present study indicate that unilateral lesions at the level of the SOC yield a pattern of behavioral deficits drastically different than those observed at higher levels within the central auditory pathway. Complete unilateral lesions of the SOC disrupt the ability to localize sound throughout the horizontal plane, with a tendency for impairments to be particularly severe ipsilateral to the lesion. The representation of auditory space at the level of the SOC, therefore, unlike that at the level of auditory cortex or the inferior colliculus, is not contralateral.

Comparison of the present results with those obtained following lesions at higher levels generally supports the notion that the SOC/TB complex functions as an acoustic chiasm whereby information concerning spatial location in the left and right hemifields is represented contralaterally at levels above the SOC. It is important to mention, however, that the representation of auditory space is not completely contralateral at the level of the auditory midbrain, suggesting that structures beyond the level of the SOC/TB complex also contribute, although to a lesser degree, to the chiasmatic process.

The difference between deficits in sound localization following unilateral SOC lesions and inferior colliculus lesions may be related to the pattern of cell loss in the SOC. Unilateral kainic acid lesions destroy all cells within SOC on

one side of the brain and result in a bilateral deficit in sound localization. In contrast, unilateral lesions of the inferior colliculus result in predominately contralateral deficits and produce retrograde degeneration within the SOC bilaterally, consistent with the pattern of anatomical connectivity with the inferior colliculus. The MSO projects ipsilaterally and the LSO projects bilaterally. Following a large unilateral lesion of the inferior colliculus severe retrograde degeneration is seen in the MSO ipsilateral to the lesion and the LSO both ipsilateral and contralateral to the lesion. Behavioral deficits following unilateral lesions of the SOC, therefore, may be attributable to a specific pattern of cell loss within the SOC.

Sensory Coding in the SOC

In some respects, the presence of severe deficits in the ability to localize sound in space following unilateral lesions of the SOC is surprising. Electrophysiological and metabolic studies would seem to indicate that the MSO is involved primarily in the coding of contralateral azimuths whereas the LSO is involved in the coding of ipsilateral azimuths (Boudreau and Tsuchitani, 1968; Caird and Klinke, 1983; Goldberg and Brown, 1968, 1969; Guinan et al., 1972a, b; Inbody and Feng, 1981; Masterton et al., 1981; Tsuchitani, 1977; Tsuchitani and Boudreau, 1969). Assuming that the MSO and the LSO operate independently, one might expect complete unilateral destruction of the SOC to have little or no effect on sound localization. With one SOC intact, the remaining MSG should be able to code for contralateral sound sources and the remaining

LSO for ipsilateral sound sources. The fact that unilateral lesions of the SOC do produce severe deficits in sound localization suggests that the SOC on the left and right side normally act in concert to provide an accurate representation of auditory space. Two theories will be considered.

First, it is possible that unilateral lesions of the SOC reduce the amount of information available for determination of sound source location. Under normal circumstances, the position of a broad band sound originating from the left of midline would be encoded by both the left LSO and the right MSO, whereas the position of a sound originating in the right hemifield would be encoded by the right LSO and the left MSO. In an animal with a unilateral lesion of the SOC, the advantage of this double representation is lost. With a left SOC lesion the left sound field will be represented by the contralateral MSO only and the right sound field will be represented by the right LSO only. Thus one possible explanation of the present results is that accurate localization of a broad band stimulus depends on the combined activity of the LSO on one side and the MSO on the other.

The second point to consider is that a unilateral lesion of the SOC might actually result in misinformation about the location of a sound source. As mentioned above, a broad band sound on the left would in a normal animal produce activity within the ipsilateral LSO and the contralateral MSO. At the same time, however, there would be an absence of neural activity within the ipsilateral MSO and the contralateral LSO.

It is quite possible that the absence of activity in these nuclei is also meaningful to the nervous system, and like the presence of activity in the above mentioned nuclei, indicate that the sound is on the left. If this interpretation is correct, one might expect the absence of neural activity resulting from a unilateral lesion of the SOC to give rise to false information regarding the location of a sound in space. Consider an animal with a unilateral lesion of the left SOC faced with the task of localizing a sound originating ipsilateral to the lesion. As in a normal animal, the contralateral MSO would be active and the ipsilateral MSO and contralateral LSO would be inactive. The ipsilateral LSO, in contrast, which under normal circumstances would be active, would in this case be inactive. Thus, although the majority of nuclei within the SOC may be signalling higher auditory centers that the sound is on the left, the LSO ipsilateral to the lesion, through its inactivity, may be telling the nervous system that the sound is not on the left but on the right. Consider now the same animal faced with the task of localizing a brief sound originating contralateral to the lesion, i.e., within the right hemifield. In this situation the ipsilateral LSO would be active and the ipsilateral MSO and contralateral LSO would be inactive, as would be expected in a normal animal if a sound were on the right. The contralateral MSO, however, which would normally be active, would be inactive. Thus the MSO contralateral to the sound source, through its inactivity, may be telling the nervous system that the sound is on the left despite that fact that it is on the right.

Considerations for Future Studies

Results of the present study indicate that complete unilateral lesions of the SOC disrupt the ability to localize a broad band stimulus throughout the horizontal plane. In explanation of the results we considered the possibility that localization of a lateralized broad band stimulus requires the concerted effort of the MSO on one side and the LSO on the other. We also considered the possibility that the absence of neural activity within the SOC is itself a code for sound location, and that the absence of activity consequent to unilateral lesions gives rise to conflicting information regarding the location of a sound in space.

Assuming either of the above theories to be true, one might predict a different pattern of behavioral deficits in animals tested with frequency-restricted stimuli. Electrophysiological studies have shown that there is a disproportionate representation of low frequencies with the MSO and high frequencies within the LSO (Guinan et al., 1972a, b; Goldberg and Brown, 1968). Thus, under appropriate stimulus conditions it might be possible to activate one nucleus independent of the other. A lateralized low frequency stimulus might be expected to drive the contralateral MSO exclusively, whereas a high frequency stimulus might be expected to drive the ipsilateral LSO exclusively.

Assuming that it is possible to activate the MSO or LSO independently, future studies might show that the pattern of behavioral deficits in animals with unilateral lesions of the

SOC depends on the frequency content of the stimulus. An animal with a unilateral lesion of the left SOC would presumably be able to localize a low frequency sound originating in the left hemifield, because position in this case would be encoded by the intact right MSO. In contrast, the animal should be incapable of localizing low frequencies originating contralateral to the lesion since the nucleus responsible for encoding position in this case, the left MSO, would be destroyed.

With a high frequency stimulus, the opposite pattern of behavioral deficits would be expected. An animal with a left SOC lesion would presumably be incapable of localizing high frequency sounds originating ipsilateral to the lesion since the nucleus responsible for encoding this information, the left LSO, would have been destroyed. In contrast one would predict no deficit in the contralateral hemifield. The nucleus responsible for encoding this information, the right LSO, would remain intact.

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Figure 1. Photomicrographs illustrating a series of caudal to rostral frontal sections at 400 micron intervals through the SOC in a normal ferret. Plate A is most caudal and plate D is most rostral. Abbreviations: MSO, medial superior olive; LSO, lateral superior olive; MNTB, medial nucleus of the trapezoid body; LNTB, lateral nucleus of the trapezoid body; VNTB, ventral nucleus of the trapezoid body; TB, trapezoid body.

Figure 2. Photomicrographs showing the appearance of the SOC in F76 following a unilateral kainic acid lesion of the right SOC. The SOC appeared normal on the left (plate A), but was completely destroyed on the right (plate B). Plates C and D show corresponding high power photomicrographs through the medial limb of the LSO. Note that there was a normal complement of healthy neurons on the left (plate C) but only gliosis on the right (plate D). For explanation of abbreviations see Fig. 1.

Figure 3. Photomicrographs showing protargol stained frontal sections through the SOC of F76, the same case shown in Figure 2. Fibers of the trapezoid body course ventral to the MSO and LSO, and through the MNTF, both contralateral (plate A) and ipsilateral (plate B) to the lesion. Plates C and D show high power photomicrographs through the left and right MNTB respectively. Note the presence of fiber fascicles on the right, despite the fact that the MNTB was completely destroyed. For explanation of abbreviations see Fig. 1.

Figure 4. Midline and lateral field performance for F75 and F84 before and after unilateral lesions which spared the SOC. Closed circles indicate preoperative performance and open circles postoperative performance. Dashed line denotes performance level expected by chance.

CONTROL LESIONS

Figure 5. Extent of damage in ferrets with complete unilateral lesions of the left SOC. Damage is illustrated at 400 micron intervals on drawings of standard frontal sections through the SOC of a normal ferret. Black shading, cross-hatching, parallel lines, and light stipple denote complete, severe, moderate and mild degeneration respectively. Numbers under each drawing indicate distance in millimeters rostral to the anterior extent of the facial nucleus. Abbreviations: MSO, medial superior olive; LSO, lateral superior olive; MNTB, medial nucleus of the trapezoid body; LNTB, lateral nucleus of the trapezoid body; VNTB, ventral nucleus of the trapezoid body; TZ, transitional zone; VNLL, ventral nucleus of the lateral lemniscus; INLL, intermediate nucleus of the lateral lemniscus; DNLL, dorsal nucleus of the lateral lemniscus; VII, facial nucleus

COMPLETE LEFT LESIONS

F154

F74

Figure 5. Continued.

F155

F77

Figure 6. Preoperative and postoperative midline and lateral field performance for ferrets with complete unilateral lesions of the left SOC. For explanation of symbols see Fig. 4

COMPLETE LEFT LESIONS

Figure 7. Extent of damage in ferrets with partial lesions of the left SOC. For explanation of symbols and abbreviations see Fig. 5.

PARTIAL LEFT LESIONS

F102

F81

Figure 8. Preoperative and postoperative midline and lateral field performance for ferrets with partial unilateral lesions of the left SOC. For explanation of symbols see Fig. 4.

PARTIAL LEFT LESIONS

Figure 9. Extent of damage in ferrets with complete unilateral lesions of the right SOC. For explanation of symbols and abbreviations see Fig. 5.

2

OF/DE

2

METRO

COMPLETE RIGHT LESIONS

F76

F129

Figure 10. Preoperative and postoperative midline and lateral field performance for ferrets with complete unilateral lesions of the right SOC. For explanation of symbols see Fig. 4.

COMPLETE RIGHT LESIONS

Figure 11. Extent of damage in ferrets with partial unilateral lesions of the right SOC. For explanation of symbols and abbreviations see Fig. 5.

PARTIAL RIGHT LESIONS

F83

F82

Figure 12. Preoperative and postoperative midline and lateral field performance for ferrets with partial unilateral lesions of the right SOC. For explanation of symbols see Fig. 4.

PARTIAL RIGHT LESIONS

Figure 13. Extent of damage in F79 following a complete bilateral lesions of the SOC. For explanation of symbols and abbreviations see Fig. 5.

COMPLETE BILATERAL LESIONS

F79

LEFT

RIGHT

Figure 14. Extent of damage in F172 following a bilateral lesion which caused extensive damage to the left SOC, but only minimal damage to the right SOC. For explanation of symbols and abbreviations see Fig 5.

PARTIAL BILATERAL LESIONS (LEFT)

F172

LEFT

RIGHT

Figure 15. Preoperative and postoperative midline and lateral field performance for F172. For explanation of symbols see Fig. 4.

PARTIAL BILATERAL LESIONS (LEFT)

Figure 16. Extent of damage in ferrets F210 and F125 following bilateral lesions which caused extensive damage to the right SOC, but only minimal damage to the left SOC. For explanation of symbols and markers see Fig. 5.

PARTIAL BILATERAL LESIONS (RIGHT)

F210

LEFT

RIGHT

Figure 16. Continued

F125

LEFT

RIGHT

Figure 17. Preoperative and postoperative midline and lateral field performance for F210 and F125.

PARTIAL BILATERAL LESIONS (RIGHT)

END

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