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Auditory Compensation of the Effects of Visual Deprivation in the Cat's Superior Colliculus*

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Summary. Neurones in the superior colliculus of normal and visually deprived cats were analyzed for their responses to visual, auditory and somatosensory stimuli. The percentage of auditory-responsive cells throughout all layers had increased from 11% to 42% after binocular deprivation. Some auditory responses were found even in superficial layers. The number of somatosensory responses, though not systematically tested, was also higher in the visually deprived animals. Visually responsive units did not significantly decrease in number, thus resulting in an increased proportion of multisensory neurones. The vigour of auditory responses had increased after visual deprivation, while the vigour of visual responses had decreased significantly. In addition to the auditory effects of visual deprivation found, our study confirms previous findings on the visual effects of visual deprivation in the superior colliculus. Since only qualitative changes of visual responses, but no suppression of visual by non-visual activity was found, the neuronal mechanisms responsible for these changes may be different from competition as present in the visual cortex.

Key words: Superior colliculus – Visual deprivation – Auditory responses – Multisensory convergence

Introduction

The critical period in the early postnatal development of vision (Wiesel and Hubel 1963; Hubel and Wiesel 1970; Blakemore and Van Sluyters 1974) is a period of high vulnerability for a developing organism. A kitten which grows up under restricted visual conditions may become blind or visually impaired on one or both eyes (Wiesel and Hubel 1963; Dews and Wiesel 1970), blind for contours of non-experienced orientations (Blakemore and Cooper 1970; Hirsch and Spinelli 1970; Hirsch 1972) or for stereoscopic information (Hubel and Wiesel 1965; Blakemore 1976). All of these defects can be demonstrated by changes both at the behavioural and at the single unit level.

Some studies have emphasized that visual experience during the critical period can also play a positive role by adapting the developing visual system to its visual environment (Barlow 1981; Rauschecker and Singer 1981; Rauschecker 1982). Despite this it can be argued that the risk of possible damage due to deprivation is probably higher than possible advantage by adaptation. This has led some authors to talk about the "paradox of the critical period" (Pettigrew 1978). This expression seems even more justified since in deprived kittens there is no convincing evidence for improvement of the remaining visual functions above normal.

There is, however, one aspect which has been largely neglected in the literature on developmental plasticity: occasional reports from the clinical literature indicate that blind or visually impaired people may develop exceptional capacities in non-visual modalities (Griesbach 1899; Woelfflin 1909). Blind people can detect texture, size, and distance of objects "by ear" rather accurately (Kellogg 1962). Moreover, they can make very efficient use of this for orientation in space. Although contradictory reports have also been made (e.g. Axelrod 1959), a recent study (Niemeyer and Starlinger 1981) using modern audiometric techniques has confirmed that blind persons show a "clear superiority at higher levels of the auditory pathways" as compared to a normal

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control group. There are hints that this marked improvement is more pronounced in persons blind from birth or who have become blind in early childhood.

Comparable investigations have not been made in blind animals. Qualitatively it appears, however, that young kittens whose eyes have been sutured shut can get along without vision surprisingly well (unpubl. observ.). Even if they are taken out of their familiar environment, they sometimes adapt to it quite fast. Since the cats can see only very coarse light/dark changes through closed eye-lids, it has to be concluded that they also use auditory and tactile cues for orientation in space.

In the same way as the effects of visual deprivation, the effects of its compensation by non-visual modalities must also be demonstrable on the single-unit level. It is well established that the midbrain tectum plays a major role in orienting behaviour (Sprague et al. 1973). Furthermore, it is a most prominent area of multisensory convergence (Wickelgren 1971). The superior colliculus, therefore, seems a most likely structure for crossmodal sensory compensation of early visual deprivation. Previous studies have presented evidence that indeed changes of this kind may be going on in the tectum (Vidyasagar 1978; Cynader 1979) or else in multisensory areas of cortex (Hyvärinen 1981).

We have analyzed responses of collicular units in superficial, intermediate and deep layers to visual, auditory and somatosensory stimuli in binocularly deprived cats and compared them to responses in normal cats. The proportion of auditory responses was found to be much higher in deprived animals. These crossmodal effects are discussed in terms of neuronal mechanisms, such as intermodal competition. The present results have previously been presented in abstract form (Rauschecker and Harris 1981).

Methods

Seven superior colliculi in six cats were studied. Two cats were binocularly deprived (BD) from birth until they were adult. A third cat (NBD) was raised in the dark until 4 weeks of age and then given 2 weeks of normal visual experience; finally both eyes were sutured shut and the cat binocularly deprived until adulthood. Three normal adult cats served as controls.

For recording all cats were anaesthetized in the same way: an initial dose of 10 mg/kg ketamine (Ketanest) plus 0.8 μg/kg Rompun (R) was given i.m., after premedication with 0.01 mg atropine s.c., a second dose of the same amount of Ketanest/Rompun 1–2 h later; then anaesthesia was continued by respiration with a 70/30 mixture of nitrous oxide/oxygen through a tracheal cannula and by i.v. infusion of 1 mg/kg h Nembutal (pentobarbital). Muscle paralysis was induced by continuous i.v. infusion of Imbretil (R) (1 mg/kg h). For nutrition a 4 : 1-mixture of glucose and Ringer solution was given through an orally inserted gastric catheter. The physical state of the animal was constantly monitored: body temperature was kept constant at 38° C, special attention was paid to the EEG, ECG, intrapulmonary pressure and expiratory CO_2-content, which was measured at the tracheal canula with a Beckman CO_2-monitor.

Sphincter and ciliaris muscles were paralyzed with atropine. The nictitating membranes were retracted with neosynephrine. The corneae were protected by black contact lenses with artificial pupils of 2 mm diameter. The refractive state of the eyes was determined with a Rodenstock refractometer and the eyes focussed on a tangent screen at 1 m distance by means of spectacle lenses. Retinal landmarks were plotted onto the screen with a Zeiss fundus camera.

In five cats we recorded from the left superior colliculi, in one cat (BD2) from the right colliculus. In cat NBD the right visual cortex (area 17) was analyzed in addition before recording from SC. In all cases 1.5 M-K-citrate filled glass micropipettes were used; only isolated single cell responses were included in the analysis.

The animals were initially held in stereotaxic coordinates with ear bars only lightly inserted, in order not to damage the ear drums. Subsequently two bolts were cemented on the frontal surface of the skull with dental cement (Paladur). A metal bar was fixed onto them which was firmly connected to the stereotaxic frame. The ear bars were then removed and the head was held by this construction plus conventional eye-holders and mouth bars. Thus, the ears were unobstructed for auditory stimulation.

Single cells in the superior colliculus were analyzed for their responses to visual, auditory, and somatosensory stimuli. Visual stimuli consisted of moving light and dark spots of various sizes and velocities; moving bars and gratings were also used. Light stimuli were produced with a hand-held projector; dark stimuli, cut out from black cardboard, were moved in front of an illuminated screen. For quantitative analysis, stimuli were generated by an optical bench system, and peri-stimulus time-histograms were produced on line by a PDP 11/34 computer. Ocular dominance was rated in five classes as defined previously (Rauschecker and Singer 1981; see also legend to Fig. 1). Direction preference and tuning were established by moving a stimulus with optimal size, velocity and light/dark polarity across the receptive field in various directions and determining the relative strengths of response in terms of spike frequency. Three classes of direction selectivity were formed: direction-selective cells (according to cortical standards) responding only within 30 deg of a preferred direction; direction-bias cells responding over a wide range of directions (sometimes through a full 360 deg), but clearly best to one of them and usually least to the opposite direction; non-directional cells responding equally to all directions of movement.

Acoustic stimuli were generated by a voltage controlled Wavetek function generator (model 154) and consisted of pure tones with usually 100 and 500 ms duration (frequency varying stepwise between 10 Hz and 50 kHz) and of clicks (0.5 ms duration). They were presented to the cats by means of ear-phones or, in free field stimulation, through a small loudspeaker (5 cm diameter) mounted on a tripod. The horizontal and vertical angular position of the loudspeaker in front of the cat could thus be varied on a concentric sphere (radius 1 m) around the centre of the cat's head, in order to determine an auditory receptive field. The sound level of the loudspeaker noises were determined with a condensor microphone close to the animals' ear and were found to be 15 dB(A) above the constant background noise of 53 dB(A) for the clicks and 32 dB(A) for the pure tones. Histograms for responses to sound stimuli were produced by the same computer program as for visual responses. In addition to the standardized stimuli, natural sounds, for example rattling a bunch of keys, tapping a pencil on the table, hissing etc. were sometimes employed.

Tactile stimuli were less easy to standardize. Usually the cat's whiskers were touched with a bar or pencil. The fur of face, legs, paws, chest and other parts of the body were touched. We tried to discriminate tonic and phasic responses. No quantitative measures by computer histograms were taken for tactile stimuli.

Briskness and reliability of responses ("response quality") was rated on a subjective scale (according to Rauschecker and Singer 1981, "1" designating the weakest and "5" the best responses.

At the end of an experiment the cats were deeply anaesthetized with Nembutal and perfused with 4% Formaldehyde. The brains were removed and cut in 50 μm sections, which were Nissl stained with cresyl violet for locating the electrode tracks and their reconstruction with respect to collicular layers. From histology it was found that the superficial and optic layers of the superior colliculus occupied on average the top 1.0 mm, which conforms with previous studies (e.g. Harris et al. 1980). Since it is not possible to make lesions with micropipettes and we did not make any dye markings, our standard criterion for assigning cells to the superficial layers was, therefore, their appearance within the first millimeter from the collicular surface as determined electrophysiologically.

Results

Normal Controls

In order to preclude any effects of different methodology it was essential for our study to establish our own baseline of collicular responses in normal adult cats. We, therefore, recorded from the superior colliculi of three controls and report about these results first.

Site of Electrode Tracks. Eight electrode passes were verified by functional and histological criteria to have been through the superior colliculi of our three control cats. Their positions are plotted in Fig. 1a in relation to an outline of the left superior colliculus. Stereotaxic coordinates varied between A 0.5–3.5 and L 3.0–3.5, respectively. In accordance with previous studies (Sterling and Wickelgren 1969; Feldon et al. 1970; Berman and Cynader 1972; Harris 1980) more posterior penetrations corresponded to positions more peripheral in the contralateral visual field. The lateral coordinates of the penetrations always corresponded roughly to positions along the horizontal meridian. The average length of the electrode tracks was 3.0 mm. Sixty-two cells throughout all layers were studied for their responses to visual, auditory and somatosensory stimuli. Twenty-two cells (35%) were from the superficial and optic layers (upper 1.0 mm of colliculus according to histology), 40 cells (65%) in the intermediate and deep layers. The median distance between recorded cells was 280 μm. A considerable proportion (18/62 = 29%) of the units did not respond to any of the stimuli applied: most of these (N = 13) were situated in intermediate and deep layers.

Visual Responses. Of all units in our normal controls 63% (39/62) responded to visual stimulation; this constitutes 89% (39/44) of all responsive units. As was found by previous authors (e.g. Sterling and Wickelgren 1969) most visual cells in the superior colliculus of normal adult cats respond to stimulation through either eye (Fig. 1b). In our sample the proportion of binocular units was 89% (35 of the 39 visually responsive cells). Ocular dominance was rated in five classes (after Rauschecker and Singer 1981; see also legend to Fig. 1b); in one cat only a binocular/monocular decision was made yielding three classes of ocular dominance.

Direction selectivity was tested in most visually responsive cells, which were then classified as direction-selective, direction-bias, or non-directional according to the criteria stated in the Methods section. The results conform with previous studies (e.g. Sterling and Wickelgren 1969; Berman and Cynader 1972; Hoffmann and Cynader 1976): Most cells (22/25 = 88%) responded best to one particular direction of movement. Virtually all cells in the superficial layers displayed this property. However, if compared to the sometimes very narrow direction tuning of cortical neurones, the direction selectivity of collicular units appears to be of a quite different quality: typically, units respond over a wide range of directions (sometimes all), but clearly best to one of them and least to the opposite direction (Sterling and Wickelgren 1969). Only 16% (4/25) of the units displayed direction selectivity according to cortical standards (responding only within about 30 deg) when tested with the optimal spot size and velocity (Fig. 1c). No cell was found which responded better or displayed narrower tuning when tested with a light or dark bar instead of a spot.

Among the cells responding best to one direction of movement (N = 22) direction preference was very often in the horizontal plane (Fig. 1d): 63% of the units responded best to such directions of movement. Most often (69%) the preferred direction also contained a vector pointing towards the contralateral periphery (cf. Sterling and Wickelgren 1969; Dreher and Hoffmann 1973). The typical direction preference (44% of the cells tested) was therefore horizontal and to the contralateral side (Fig. 1d).

Visual responses were generally brisker and more reliable in the superficial than in the intermediate and deep layers. Those cells which were assigned to the superficial layers by our criteria had a response quality score (see Methods) of 3.9. The average score of response quality over all layers was 3.3. This difference in response qualities of cells in different layers was highly significant ($X = 10.9$; $p < 0.001$).

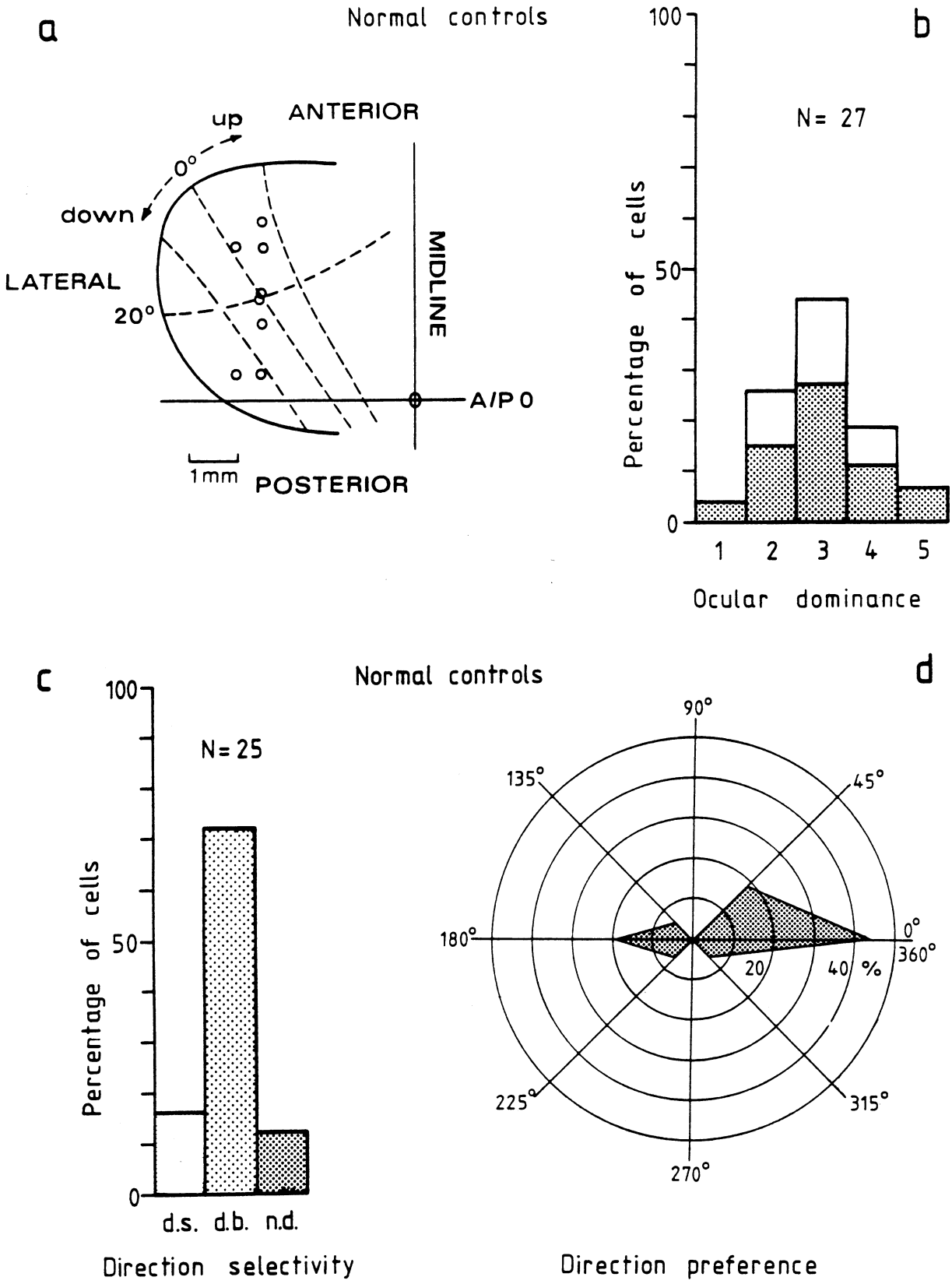

a
Normal controls
up
ANTERIOR
0°
down
LATERAL
20°
MIDLINE
A/P 0
1mm
POSTERIOR
b
100
50
0
N= 27
Percentage of cells
1 2 3 4 5
Ocular dominance
c
Normal controls
100
50
0
N= 25
Percentage of cells
d.s. d.b. n.d.
Direction selectivity
d
90°
135°
45°
180°
0°
360°
225°
315°
270°
20
40 %
Direction preference

Fig. 1a–d

Auditory Responses. Eleven percent (7/62) of all cells analyzed in our normal cats responded to auditory stimuli. All of them were situated in the intermediate and deep layers of superior colliculus. No cells in the superficial layers responded to auditory stimuli.

If possible, the aural dominance of a neurone and the location of its auditory receptive field (RF) were determined. The borders of an auditory RF were found by placing the sound source in different angular positions around the centre of the cat's head at constant distances. This was obviously only possible when a loudspeaker, but not when earphones were used. As found by previous authors (Wickelgren 1971; Harris et al. 1980) the location of the auditory RF usually matched quite well the location of a visual RF, if present. Often the auditory RF was localizable precisely only in its horizontal extent, but not in its upper and lower borders.

As far as discernable with our means, auditory cells usually responded to stimulation through either ear, but always better through the contralateral one. Due to the low number of auditory cells (N = 7) no further classification of response types was attempted in the normal animals. However, there appeared to be no fundamental difference to the types described below for the deprived animals.

Somatosensory Responses. Responses to somatosensory stimulation were not routinely checked in all three control cats. Their proportion was therefore certainly underestimated. Of all cells examined 8% (5/62) responded to touching the contralateral side of the animal with a bar or pencil. Responses were always of a transient type, i.e. even if the stimulus was maintained, only onset and/or offset elicited a response.

Visually Deprived Cats

We recorded from the superior colliculi of three visually deprived cats in order to see whether any changes had occurred in the quality or proportion of auditory or somatosensory responses as a result of visual pattern deprivation during early development.

Two cats were completely deprived of pattern vision by suturing their eyes from birth until more than six months of age. One cat (NBD) had a period of 7 weeks of normal vision around the age of 5 weeks preceded and followed by total visual pattern deprivation. The visual cortex (area 17) of cat NBD was also recorded from and the cells' responses resembled very closely those of a cat pattern-deprived throughout the critical period (Rauschecker and Singer 1982): 52% of the cortical cells did not respond to visual stimuli at all or responded only weakly (response qualities 1 and 2); 79% of those that did respond responded to all orientations.

Site of Electrode Tracks. We recorded 121 neurones from the superior colliculi of the three experimental animals. The tracks had an average length of 3.2 mm. Fifty-four cells (45%) were situated in the superficial and optic layers (upper 1.0 mm), 67 cells (55%) in the intermediate and deep layers. The median distance between recorded neurones was 240 μm.

Auditory (and somatosensory) responses in intermediate and deep layers have been reported preferentially in more lateral and possibly posterior portions of colliculus, which correspond to the more peripheral and downward segments of the visual and auditory field (Wickelgren 1971; Gordon 1973). Anatomically also a higher density of projections from the inferior colliculus is found to the lateral and caudal parts of superior colliculus (Edwards et al. 1979). We, therefore, decided to work against this trend and chose recording sites not more posterior than A 2; only one penetration was more lateral than L 3.2. Figure 2a gives the locations of the nine recording tracks in all three experimental animals, again projected onto the horizontal outline of the left colliculus. All visual and auditory receptive fields were within 20 deg of the midline (in agreement with previous studies: Feldon et al. 1970; Harris 1980). A reconstruction of a typical electrode track is shown in Fig. 2b: cellular activity and responses are given in relation to the different colliculuar layers. This track contains two bimodal cells (visual plus auditory) in the superficial layers; the intermediate layers contain no visual, but a number of totally unresponsive units.

Fig. 1a–d. Visual responses in superior colliculus of three normal adult control cats. **a** Site of the eight electrode penetrations projected onto an outline of the left superior colliculus. **b** Ocular dominance distribution (1 = monocular contralateral, 2 = contralaterally dominated, 3 = symmetric binocular, 4 = ipsilaterally dominated, 5 = monocular ipsilateral); *open blocks* = control cat 1, *stippled blocks* = control cats 2 and 3. **c** Direction selectivity of collicular units for a moving spot of light (d.s. = direction selective according to cortical standards responding only within 30 deg; d.b. = direction-bias responding best to one direction of movement but also to other directions; n.d. = non-directional responding equally to all directions). **d** Polar diagram of direction preference indicating the percentage of cells responding best to one particular direction of movement

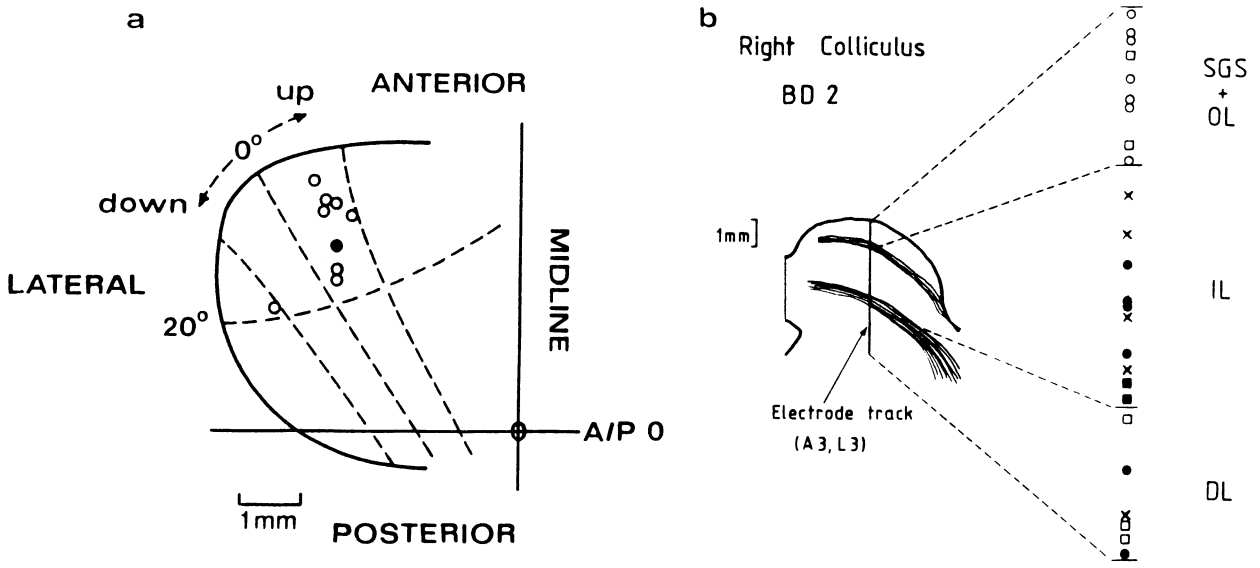


Fig. 2a, b. Electrode tracks in the three visually deprived cats. **a** Site of electrode penetrations projected onto an outline of the left superior colliculus. One penetration was located in the right colliculus and is displayed mirror-imaged in the same figure (*filled symbol*). **b** An example of a typical electrode track through the right superior colliculus schematically reconstructed from histological sections with regard to collicular layers (SGS: superficial grey substance; OL: optic layer; IL: intermediate layer; DL: deep layer). *Open symbols* correspond to visually responsive units, *filled symbols* to units responding to non-visual modalities. *Circles* represent unimodal cells and *squares* bi- or multimodal cells. Totally unresponsive neurones are indicated by *crosses*

Change in Visual Responses. Out of our sample of 121 cells, 109 were analyzed fully. Twenty-five units (25/109 = 23%) did not respond to any of our visual, auditory or somatosensory stimuli and were termed totally unresponsive. The large majority of the units analyzed (66/109 = 61%) still responded to visual stimuli.

The ocular dominance of visual responses was shifted very strongly to the contralateral eye in all three binocularly deprived cats (Fig. 3a). No cells at all were dominated or exclusively driven by the ipsilateral eye, 74% (35 out of 47 cells analyzed for ocular dominance) were exclusively driven by the contralateral eye. The shift to the contralateral eye was slightly less pronounced in cat NBD (which had had an intermittent period of normal vision), but even in this animal no cells were dominated or exclusively driven by the ipsilateral eye.

Very striking also was the drop in direction selectivity of visual responses after binocular deprivation (Fig. 3c): almost half (22/48 = 45%) of the visual cells tested for direction selectivity did not display a preference for a certain direction of movement. However, 15% of the cells (7/48) still showed narrow directional tuning (according to cortical standards): the same percentage as in our normal control cats. The increased proportion of non-directional units was mainly due to a decrease in direction-bias units, which dropped from 72 to 40%.

No change was found in the preference of collicular units for horizontal directions: 80% of the visual cells which showed a preference responded best to horizontal stimulus movement. 73% responded best to movement towards the contralateral periphery, the largest group (61%) being constituted by horizontal direction preference to the contralateral side (Fig. 3d). An example of responses of a typical cell displaying such a direction preference is shown in Fig. 3b.

In general, visual responses were less brisk and reliable than those of the colliculi of normal cats. Out of 36 units for which "response quality" was determined, 13 (= 36%) fell into the lowest category 1. The average score of response quality was 2.3, which

Fig. 3a–d. Visual responses in superior colliculus of the three visually deprived cats. **a** Ocular dominance distribution (for ocular dominance classes see Fig. 1); *open blocks* = cat NBD with 2 weeks of normal visual experience preceding deprivation, *stippled blocks* = cats with total visual pattern deprivation. **b** Example of responses of a typical direction-bias unit in the superficial layers responding best to horizontal movement towards the contralateral side, but also to other directions of a moving light spot stimulus. The same cell was transiently inhibited by auditory stimuli. **c** Direction selectivity and **d** Direction preference of collicular units (conventions as in Fig. 1)

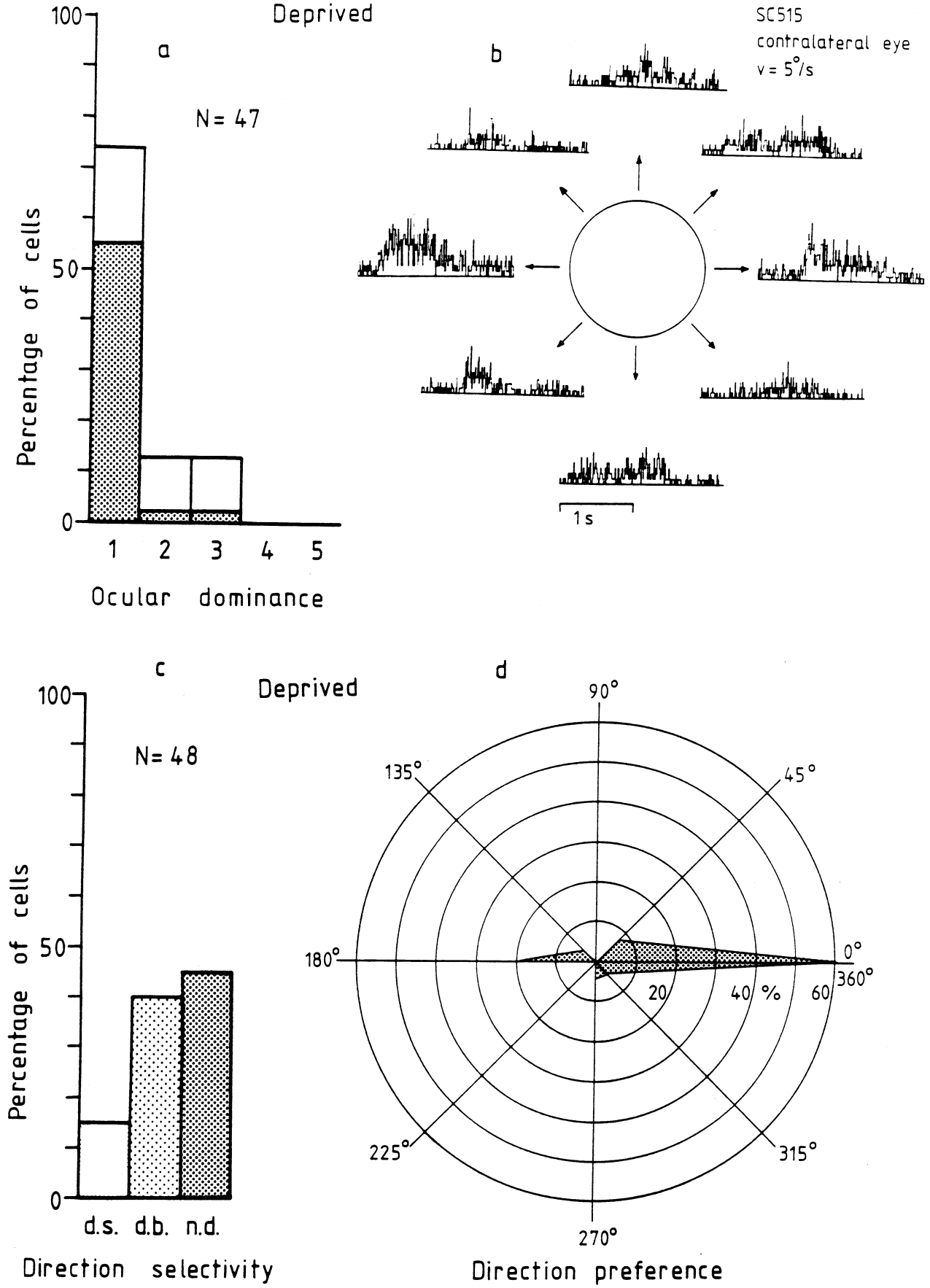

Deprived
a
N= 47
100
50
0
Percentage of cells
1 2 3 4 5
Ocular dominance
b
SC515
contralateral eye
v= 5°/s
1s
c
Deprived
N= 48
100
50
0
Percentage of cells
d.s. d.b. n.d.
Direction selectivity
d
90°
135°
45°
180°
0°
360°
225°
315°
270°
20
40 %
60
Direction preference

Fig. 3a–d

is significantly below that for the normal controls (chi-square test; $p < 0.001$).

Auditory Responses. Auditory responses were found more often and were more vigorous in visually deprived cats. Out of 103 units tested with acoustic stimuli, 46 (= 45%) showed a response. This represents 55% of the 84 cells that responded to any of the three modalities tested. Most of these auditory neurones responded to other sensory stimuli as well: 26/46 = 57% responded to both visual and auditory stimul, 2/46 = 4% to both somatosensory and auditory stimuli, and 5/46 = 11% to all three modalities. However, the most vigorous auditory responses came from neurones which did not respond to visual stimulation.

In cells responding to both visual and auditory stimuli, the receptive field centres were in general roughly superimposed. The size of the auditory RF, however, often appeared much bigger, sometimes extending over the whole contralateral hemi-field. We did not routinely test whether moving acoustic stimuli yielded better responses than stationary ones; therefore, we cannot say with certainty that for example directional preference or tuning were the same for both modalities. In a few examples we got the strong impression that this was the case, as has been suggested by previous studies in normal cats (Gordon 1973).

For some auditory neurones we attempted to establish a measure equivalent to ocular dominance: this aural dominance can be determined safely only by use of earphones. However, differences of excitability through the two ears may also be found with loudspeakers using low sound intensities. We measured the aural dominance of 16 cells in one of these ways using a scale of 1–3 (Fig. 4a). Most cells (10/16 = 63%) were activated more strongly through the contralateral than through the ipsilateral ear. This is illustrated in Fig. 4b.

As in the normal animals, two kinds of auditory responses could be discriminated, typical examples of which are shown in Fig. 4c and d. The commonest type of response (37/46 = 80%) was excitatory to a click or short tone burst over a wide range of frequencies. These units responded to a prolonged tone burst only with a transient volley of spikes at its onset and maintained their spontaneous rate throughout the rest of the presentation. This transient "on-excitation" had a peak latency of 10–20 ms in the different cells. When the tone was switched off, these cells were either inhibited (followed sometimes by a rebound of spike activity) or responded to the offset (on/off-excitation). The "off-response" was usually smaller and had a slightly longer latency than the "on-response". Switching off or on a constant background noise had the same effect and also resulted in a response. Correspondingly, the frequency selectivity of these cells was very broad: units would respond to a range of frequencies between 500 Hz and 50 kHz, sometimes with multiple peaks similar to "multirange" units in auditory cortex (Abeles and Goldstein 1972). The example in Fig. 4c had a response maximum at around 7 kHz and showed secondary maxima at 15 and possibly 30 kHz, which correspond roughly to the even harmonics of this frequency. All these "broad-band cells" responded well to complex sounds containing a broad spectrum of frequencies, like hissing or rustling. No cells with narrow frequency tuning were found.

A second type of auditory response we encountered (9/46 = 20%) appeared to be of a purely inhibitory nature. Preferentially following clicks or short tone bursts cells of this kind would stop firing sometimes completely for a period of 5–50 ms. The outset latency of the inhibition was sometimes smaller than 20 ms, but usually much longer (30–50 ms). An example is shown in Fig. 4d. If prolonged tone bursts were used, such inhibitory responses were found only at their onset, but not at their offset.

Binaural neurones most often received an excitatory input from either ear (EE cells). Occasionally an excitatory response was found to sound stimulation from one side and inhibition following stimulation from the opposite side (EI cells). This kind of binaural interaction can be demonstrated already on more peripheral levels of the auditory pathway (Goldberg and Brown 1968) and is discussed as a possible basis for sound localization. Due to the low number of auditory responses in our normal controls

Fig. 4a–d. Auditory responses in the superior colliculus of visually deprived cats. **a** Aural dominance distribution (1 = exclusively or predominantly contralateral, 2 = symmetric binaural, 3 = exclusively or predominantly ipsilateral). For further explanations see text. **b** Examples of peristimulus response histograms to auditory stimulation. The cell was recorded from the right superior colliculus. Auditory stimuli were presented using small loudspeakers in three different locations, as indicated, at a constant distance of 1 m. Peak firing rates and integrated responses over 100 ms are given. **c** Frequency selectivity of a typical excitatory deep layer cell response (cat BD2) to tone bursts of 100 ms duration presented through a small loudspeaker. The same cell did not respond to visual stimulation, but had a somatosensory receptive field on the contralateral side of the nose. **d** Inhibitory responses of a deep layer cell (cat BD1) to two tones of different frequency

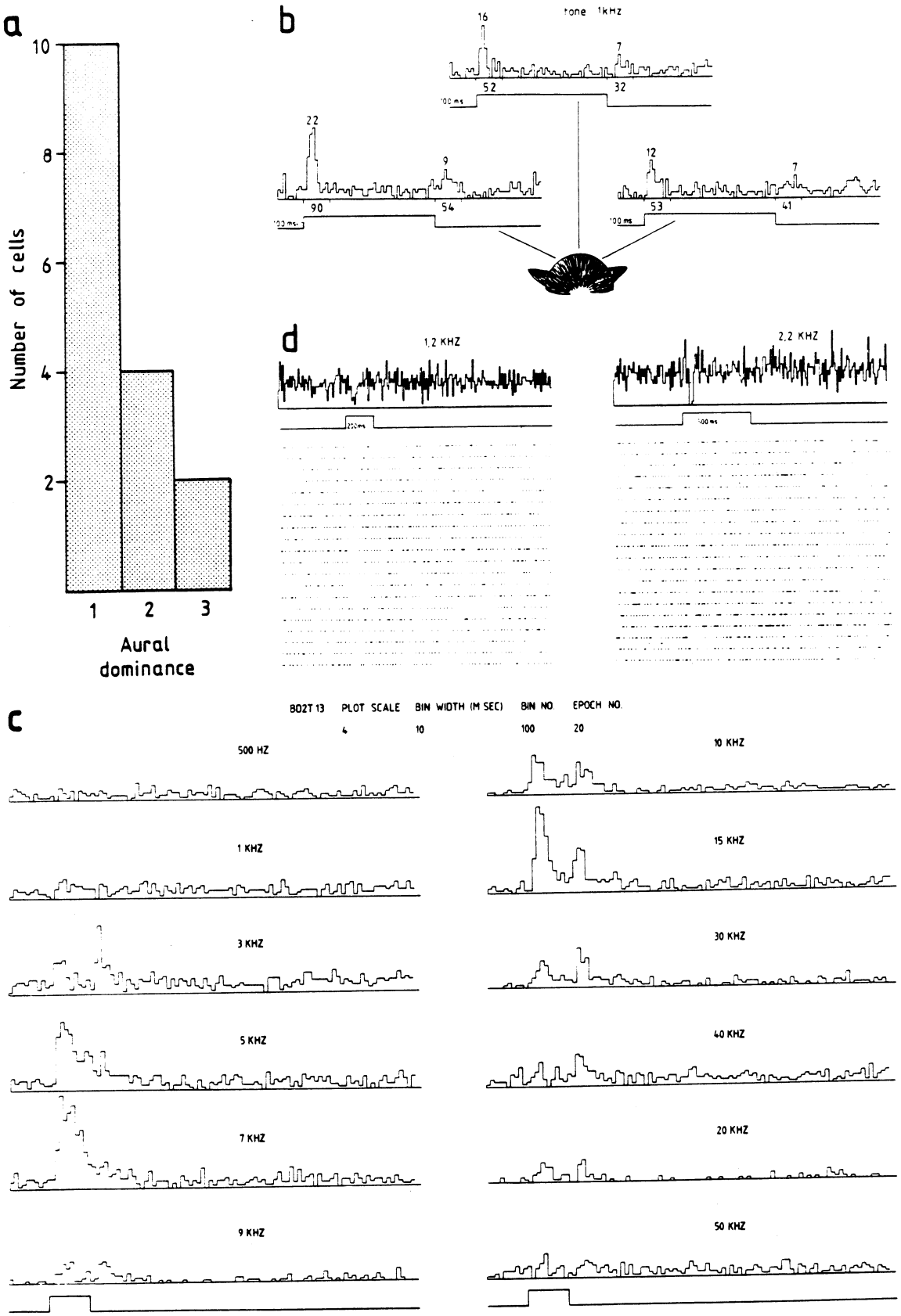
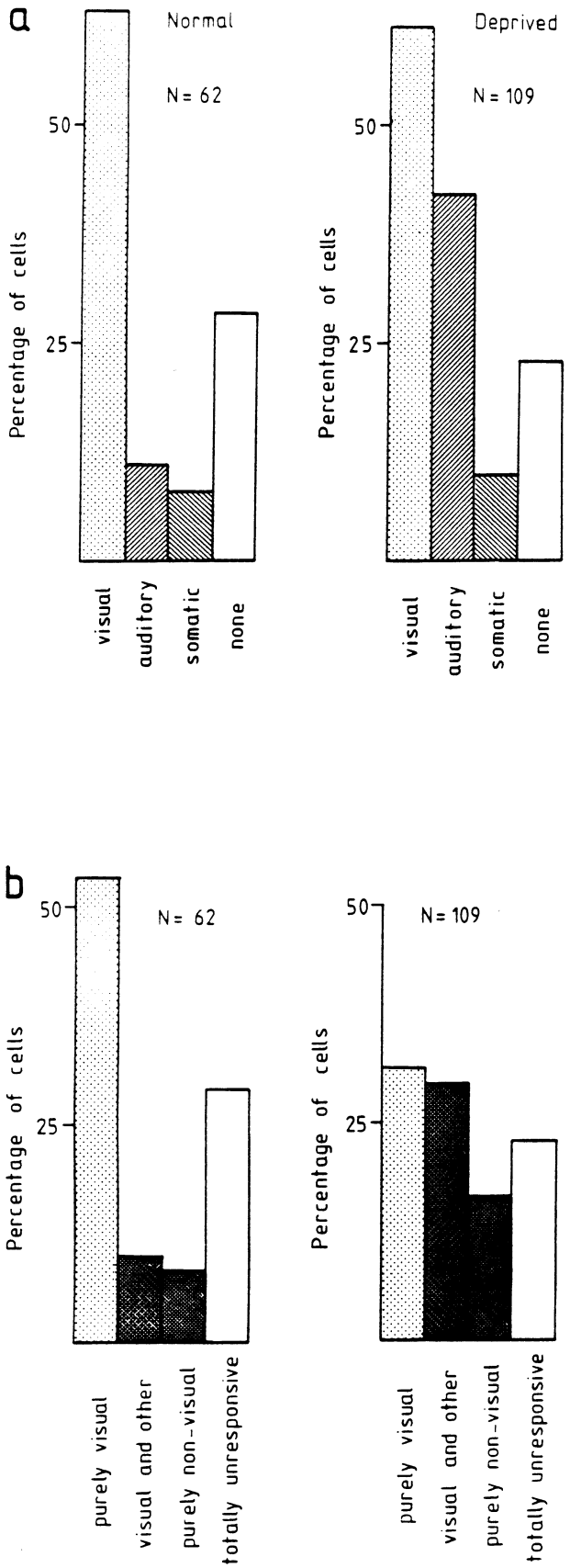

a
Number of cells
10
8
6
4
2
1
2
3
Aural dominance
b
tone 1kHz
16
7
52
32
22
9
90
54
12
7
53
41
d
1.2 KHZ
2.2 KHZ
c
B02T13 PLOT SCALE BIN WIDTH (M SEC) BIN NO. EPOCH NO.
4 10 100 20
500 HZ
1 KHZ
3 KHZ
5 KHZ
7 KHZ
9 KHZ
10 KHZ
15 KHZ
30 KHZ
40 KHZ
20 KHZ
50 KHZ

Fig. 4a–d



it is hard to decide whether the proportion of these units was actually increased in the visually deprived animals.

Some indication of interactions between visual and auditory responses (attenuation or facilitation) were also observed, but were not further substantiated.

Somatosensory Responses. As in our normal controls, somatosensory stimuli were only applied last, often after the effects of visual and auditory stimulation had been extensively tested. Many units were not checked for somatosensory responses. Their number will, therefore, be greatly underestimated. Out of 73 units tested with somatosensory stimuli, only 11 (= 15%) responded to them. As in the normal cats, receptive fields were always on the contralateral half of the body, usually on foreleg, face or chest. Surprisingly, in our sample no cell was found which responded to stimulation of the whiskers (c.f. Dräger and Hubel 1975).

No change was observed in the response types of somatosensory cells, as compared to normal: Responses were always transient, i.e. the cells responded to the initiation or release of light pressure stimuli. Cells preferred moving to stationary stimuli. Care was taken not to confuse somatosensory with auditory responses by applying touch rather than tapping stimuli to the fur and by precisely localizing a receptive field on the body surface.

Proportion of Visual, Auditory and Somatosensory Cells in Normal and Deprived Cats

The main finding of our study is the enormous increase of auditory responses in visually deprived cats. At the same time the number of visual responses was not significantly reduced. Slightly less neurones were found that did not respond to any of the stimuli available.

Fig. 5a, b. Proportions of visual, auditory and somatosensory responses in the superior colliculus of normal and visually deprived cats. **a** Proportions of cells responding to the different modalities. The number of auditory-responsive cells is highly increased in the visually deprived cats. Notice that the total exceed 100% because of the multiple inclusion of multi-sensory cells. **b** Mutually exclusive categories are formed by separating uni- and multimodal cells. In the visually deprived cats the number of units responding to both visual and auditory stimuli has increased, apparently at the expense of purely visual ones

These results are synoptically presented in Fig. 5. It can be seen from Fig. 5a that the proportion of visual cells was roughly the same in both groups of animals (63 and 61%, respectively), whereas the proportion of auditory cells was much higher (42%) in the visually deprived than in the normal cats (11%). This difference is significant at the 1% level (chi-square test). The number of somatosensory responses in superior colliculus did not increase by the same amount after visual deprivation: 10% of all cells responded to touch stimuli as compared to 8% in our controls. It needs to be emphasized once again, however, that somatosensory responses were not always checked systematically. Somewhat surprising, if one thinks of the effect of visual deprivation on visual cortex, was the lack of increase of unresponsive cells in the deprived colliculi. Only 23% of the units tested were totally unresponsive, while in the normal colliculi 29% did not respond to any of our sensory stimuli, However, as mentioned above, a clear deterioration of response qualities was found.

The percentages in Fig. 5a do not add up to 100% since bi- or multimodal cells show up two or three times, respectively. Mutually exclusive categories can be formed by separating uni- and multimodal cells (Fig. 5b). With this method of presentation it becomes clear that the proportion of purely visual responses has dropped dramatically from 53 to 31% in the visually deprived cats. At the same time the number of multimodal responses including vision has increased almost three-fold from 10 to 29%; and the number of purely non-visual (auditory or somatosensory) responses has more than doubled from 8 to 17%. The percentage of totally unresponsive units remains the same as in the previous figure.

Some quantitative difference was detectable between the cats that were visually deprived throughout their life (BD) and the cat that had received some normal visual experience around five weeks of age (NBD). In this cat the proportion of purely non-visual cells was only 8% (as in the normal controls) of all analyzed cells, while in the two BD cats this proportion was 21%. The number of multimodal cells including vision was 34% in cat NBD and 27% in the two BD cats. In particular, 73% of all auditory units in cat NBD also responded to vision, while this proportion was only 48% in the two BD cats. It seems, therefore, that the short period of normal vision had helped to keep up the relative strength of visual input to the superior colliculus somewhat more than complete lack of pattern vision. One may speculate whether rearing in total darkness from birth could reduce the number of visual responses even more.

Discussion

The superior colliculus in the midbrain tectum is a nucleus of multimodal convergence and seems to play a major role in orienting behaviour and localization (Sprague et al. 1973; Wurtz and Mohler 1976). The aim of the present study was to look for evidence whether at least partial compensation is achieved by other sensory modalities for the lost orienting capacity of vision following early blindness. Before the evidence from our data for such partial compensation is discussed, some methodological considerations are inevitable.

Anaesthesia and Arousal Level

We were concerned that some of our results could be due to the effect of anaesthesia. The level of anaesthesia has been shown to affect the responsiveness of collicular neurones (especially in intermediate and deep layers: Sterling and Wickelgren 1969). We, therefore, took greatest care that anaesthesia was done in exactly the same way in all animals. We monitored EEG, ECG and expiratory CO_2 and could tell no difference in the level of anaesthesia between animals.

Nevertheless, one might be inclined to attribute the reduced number of unresponsive cells and the increased number of auditory responses to different levels of anaesthesia in the two groups of animals. That this is unlikely to be the reason is suggested by two facts: First, the increase in the number of auditory responsive units appeared to be quite selective; the number of visual cells did not grow by the same amount, which might be expected if anaesthesia had been lighter in the deprived cats. Second, the vigour of visual responses was found to be decreased significantly as compared to normal. If the changes found were not the result of visual deprivation, but simply the result of different levels of anaesthesia or arousal, the vigour of visual responses would have been expected to increase rather than decrease.

Another point needs to be mentioned in this context. Loud and sudden stimuli can themselves act as excellent sources of arousal. It might be argued, therefore, that the responses to sound stimulation were in fact only a result of reticular activation rather than a specific sensory response. Although we cannot exclude this possibility in all cases, it cannot be used as an explanation for responses in which an auditory receptive field or aural dominance could be determined, as described above. This was true for nearly all auditory cells in the deprived animals. Besides, this argument applies to both groups of animals and, therefore, cannot explain the difference found.

Sampling Bias in Different Layers

Another possible explanation for the augmented occurrence of auditory cells might be that perhaps systematically more units were isolated in the intermediate and deep layers in the deprived animals.

The main argument against such a layer-specific sampling bias is that the proportion of units from intermediate and deep layers determined from track analysis was, in fact, slightly lower in the deprived cats than in the normal controls (55% versus 65%). Besides, the recording density of single neurones was calculated for each penetration. While the median distance between recorded neurones was on average slightly less in the deprived cats (although this difference was not significant), no significant difference was found between the recording density of upper and lower layers. Indeed a sampling bias in favour of deep layer units would have to be quite enormous (given the normal proportion of auditory units) to explain our observed incidence of auditory neurones.

A further observation suggesting a real increase in auditory responsive cells are the few cases of auditory responses in superficial layers of colliculus in the visually deprived cats. The occurrence of such cells was surprising to us, but despite some uncertainties due to possible dimpling of the collicular surface it seems quite clear from track analysis that these units were actually located in the superficial or optic layers, respectively (see for example Fig. 2B). In fact, auditory fibres from auditory area A II and the suprasylvian fringe cortex have been shown to terminate in the superficial layers of superior colliculus (Paula-Barbosa and Sousa-Pinto 1973). It seems possible that this potential source of auditory activity is ineffective in normal cats, but can dominate the response of some cells after visual deprivation.

Visual Effects of Visual Deprivation

From the above considerations we feel secure enough to believe that our data reflect indeed the results of functional changes occurring in superior colliculus during visual deprivation.

Our study clearly confirms previous studies that have shown that binocular deprivation results in dramatic changes of the visual response properties in the superior colliculus: the binocularity of collicular units, which normally develops during the first weeks of life (Stein et al. 1973; Norton 1974), is almost totally lost and their direction selectivity is much reduced. Both these changes may be explained as an indirect effect due to changes in the visual cortex (Hoffmann and Sherman 1975): binocular deprivation reduces the excitability and specificity of cortical neurones which in turn weakens the (mainly ipsilateral) cortical influence on the superior colliculus, which is left with its (mainly contralateral) retinal input and with reduced direction selectivity. In our study, however, direction selectivity of collicular units, unlike their binocularity, was not totally lost. In particular, the proportion of cells with narrow directional tuning remained with 15 vs. 16% practically unchanged. If possible residues of selectivity in deprived cortex are neglected, this suggests that circuits exist either within the tectum or in other nuclei providing input to the tectum capable of constructing direction selectivity without cortical aid. Such a conclusion is at variance with previous authors who have suggested that direction selectivity of collicular neurones is exclusively determined by cortical input (Wickelgren and Sterling 1969; from cortical ablation experiments) and supports other studies emphasizing non-cortical, possibly intracollicular mechanisms (Hoffmann and Cynader 1976).

Our data also show for the first time that the vigour and reliability ("response quality") of visual collicular responses is much reduced by binocular deprivation. This may indeed also be explained as an indirect effect due to changes within the visual cortex whose excitability is well known to be reduced by deprivation and in turn exerts less of its excitatory influence (McIlwain and Fields 1970) on superior colliculus.

Auditory Effects of Visual Deprivation

Binocular deprivation thus results in a dramatic deterioration of visual response properties in superior colliculus. Most of these *intra*modal changes seem to be due to an indirect effect through the visual cortex (Hoffmann and Sherman 1975). This has been taken to suggest that neuronal networks in the tectum proper might be more rigid than neocortical structures and less susceptible to shaping of their response properties by epigenetic factors. This view seems to fit the fact that the midbrain is a phylogenetically older structure, which might not be so well equipped with a "recent" invention of learning and plasticity.

Our findings of *inter*modal effects from deprivation cast some doubt on this traditional interpretation. Even if the visual effects of visual deprivation are mainly indirect, the dramatic increase of auditory responses after visual deprivation suggests that a functional reorganisation of afferent input might have occurred within the tectum. The augmented

incidence of auditory responses cannot be a relative change, i.e. simply an increased probability of recording auditory cells due to a loss of visual cells. This is excluded by the fact that most auditory cells in our visually deprived animals still had an additional visual input. Thus, the auditory input seems to have developed during visual deprivation and innervated cells that would have been purely visual under normal circumstances.

It may well be that even in normal cats a lot of cells, at least in intermediate and deep layers, do possess an additional auditory input. They may, therefore, have the potential ability to respond to auditory stimuli, but this may not be potent enough to be recorded. Visual deprivation may thus only unravel or strengthen "hidden" synaptic inputs which are present anyway. This may even hold as an explanation for the few auditory responses that we found in the superficial layers, since anatomically an auditory input seems to be present (Paula-Barbosa and Sousa-Pinto 1973). Auditory-responsive units in these layers, however, have never been reported in normal cats. This makes it attractive to consider as an alternative hypothesis that actual plastic rearrangement of neuronal circuitry in the midbrain tectum, e.g. sprouting of auditory afferents, has taken place.

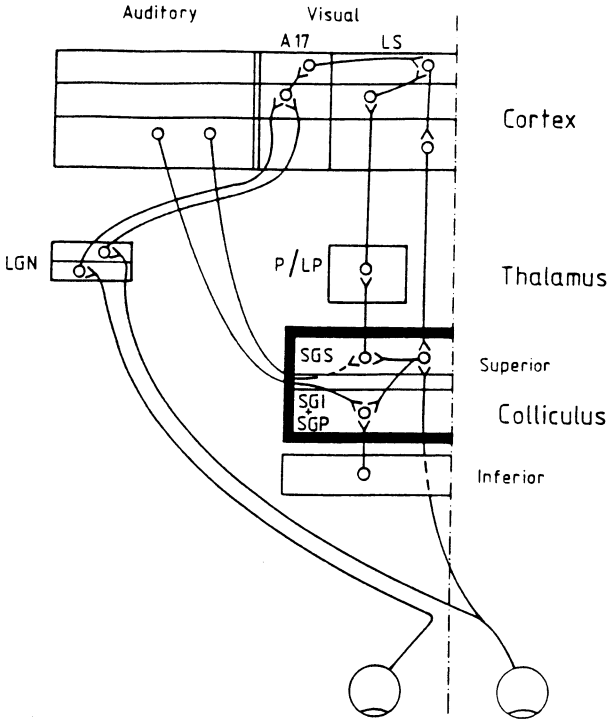


Fig. 6. Scheme of connexions illustrating possible neuronal pathways and mechanisms through which partial auditory compensation of the effects of visual deprivation in superior colliculus might occur. A direct route through the inferior colliculus and an indirect one through the auditory cortex are discussed. A 17 = area 17; LS = lateral suprasylvian areas; LGN = lateral geniculate nucleus; P/LP = pulvinar/lateralis posterior complex; SGS, SGI, SGP = stratum griseum superficiale, intermedium, profundum

Mechanisms of Intermodal Compensation

Neuronal competition is a major mechanism explaining changes of ocular dominance in visual cortex during early development (Wiesel and Hubel 1965; Guillery 1972; Sherman et al. 1974). The same mechanism can be applied in a modified form also to changes in cortical orientation preferences and can be seen as a special case of synaptic plasticity involving postsynaptic structures (Rauschecker 1979; Rauschecker and Singer 1979, 1981; Rauschecker et al. 1981). Can competition between different sets of afferents explain the changes in the superior colliculus we describe here?

A competitive mechanism requires the suppression of one set of afferents by another which is more successfully activated. Binocular deprivation would indeed offer non-visual afferents a relative advantage over visual afferents at least in the multisensory, deep layers of the colliculus (Cynader 1979). However, unlike in the reports of Vidyasagar (1978) in the rat and Cynader (1979) in the cat no quantitative suppression of visual by non-visual activity was found in our study, except possibly for the intermediate layers in some penetrations (see for example Fig. 2b). Instead, auditory responses were recorded in addition to visual ones, which had deteriorated only in "quality" (response vigor and feature selectivity). Of course, this deterioration may also be interpreted as partial suppression.

Although the complete neuroanatomy is far from clear, a tentative scheme is presented in Fig. 6 to illustrate a possible mechanism which does not necessarily involve neuronal competition. Auditory afferents to the superior colliculus are successfully activated during visual deprivation. According to algorithms presented previously (Rauschecker and Singer 1979, 1981; Rauschecker et al. 1981) their synaptic weight gets strengthened as a result of this successful activation. By contrast, visual afferents to the superior colliculus – both direct and indirect – are, of course, not driven by patterned stimuli during the deprivation. According to the rules of competition the collicular synapses involved in visual connexions should become weakened. This is indeed the case for the indirect ipsilateral pathway, which normally establishes binocularity in the superior colliculus. It may well be that this weakening of the ipsilateral input is partly due to competition between visual and

non-visual afferents in the colliculus rather than to disconnection already at the cortical level. However, we find also that the direct contralateral pathway remains effective despite successful activation of the competing auditory pathway. Thus, it appears that the midbrain tectum has the ability to maintain or strengthen some synaptic connexions without "unlearning" other established circuitry via competition. Alternatively, a more complex mechanism could be thought of involving once more indirect cortical pathways: in such a model the changes found in superior colliculus would reflect rearrangements in higher cortical association areas (cf. Hyvärinen 1981 for enhanced somatosensory activity in visual associative cortex area 19 of visually deprived monkeys).

In conclusion, partial compensation of neural defects resulting from deprivation in one sensory modality has been shown to occur by other senses in the midbrain tectum. This finding adds a new twist to our understanding of the vulnerable critical period in early vision, which has often been considered so paradoxical (Pettigrew 1978). Critical periods in early postnatal development seem to offer the possibility for a reduction of redundancy and an optimization of information capacity in the brain of mammals.

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