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LONG-LASTING NERVOUS SYSTEM RESPONSES TO PROLONGED SOUND STIMULATION IN WAKING CATS

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INTRODUCTION

MOST NEUROPHYSIOLOGICAL EXPERIMENTS deal with phenomena which last for only a brief period of time, usually measured in milliseconds or seconds. Commonplace subjective experience, however, indicates that longer lasting effects may follow prolonged periods of sensory stimulation. Sensations of motion, for example, may last for hours or days following a rough sea voyage (for a vivid description of this effect see ref. 17). The French refer to this as *mal de débarquement*. Analogously persisting aftereffects are observed in the visual system (e.g., the "waterfall effect") and auditory and somesthetic systems. We presume that neurophysiological events must underlie these illusions.

The present experiments were designed to record electrical activity taking place along the auditory pathway before, during, and after prolonged sound stimulation, in order to observe whatever neurophysiological aftereffects may follow long-lasting stimulation. In addition to aftereffects, we found other phenomena which merit analysis in their own right.

METHODS

Adult cats were repeatedly exposed to loud white noise. Electrical activity was monitored from a variety of electrode sites before, during, and after sound exposure. The electrodes were made up of two 36-gauge enameled wires twisted tightly together, with their bared tips separated vertically by 1 mm. These were cemented to the skull and brought together through a pedestal according to techniques adapted from Sheatz (23). Cortical bipolar electrodes rested on the pia. In some animals a monopolar stainless steel spring electrode was cemented to the bulla so that the bared spiral ending of the spring touched the round window, according to techniques of Galambos and Rupert (8). Four recording sites were established in each animal. Microscopically verified electrode placements along the auditory system included cochlear nucleus, trapezoid body, superior olive, inferior colliculus, brachium of the inferior colliculus, medial geniculate body, and auditory cortex. Control recording sites included cerebellar cortex, dentate nucleus, principal nucleus of the trigeminal, midbrain reticular formation, red nucleus, superior colliculus, thalamic nuclei *ventralis lateralis* and *ventralis posterolateralis*, anterior hypothalamus, amygdala, and striate, association and sensorimotor cortex. Inadvertent control placements included the pontine portion of the ventral spinocerebellar tract, restiform body, brachium conjunctivum, and lateral geniculate body.

The cats were allowed to recover for at least a week following electrode implantation. Sound exposure took place in a sound-attenuating room where the animals were free to move about within a small chicken-wire cage. They were observed through a one-way mirror from an adjacent recording room. A flexible Microdot cable, attachable to the recording pedestal, led to four condenser-coupled Tektronix type 122 amplifiers, with band pass set at 0.2-10 kc. These amplified signals were delivered to four summators of a design

diagrammed in Fig. 1, modified from an original circuit by Beidler (3). The outputs were recorded on Esterline-Angus DC milliammeters. Illustrations and most of the summator data for this paper were obtained using the design shown in Fig. 1A. Later, Dr. Ichiji Tasaki designed an improved summator (Fig. 1B). This yields the same qualitative and essentially the same quantitative results in these experiments, but is more linear and is also useful for integration of activity from only a few or single units. Summated records were obtained continuously during a 2-hour control period, a 2-hour exposure to loud white noise, and a 4-hour period following discontinuation of sound. Signals entering the summator were viewed on a Tektronix 535A oscilloscope which operated an enclosed slave oscilloscope used for photographic purposes. These photographs provided detailed comparison and correlation with the summated records. Similar procedures were followed in the same animals both awake and anesthetized (using Nembutal 25 mg/kg. intraperitoneally initially, and approximately one-third of that dose repeated hourly). Repeitions of these experiments were conducted on each animal over a period of months.

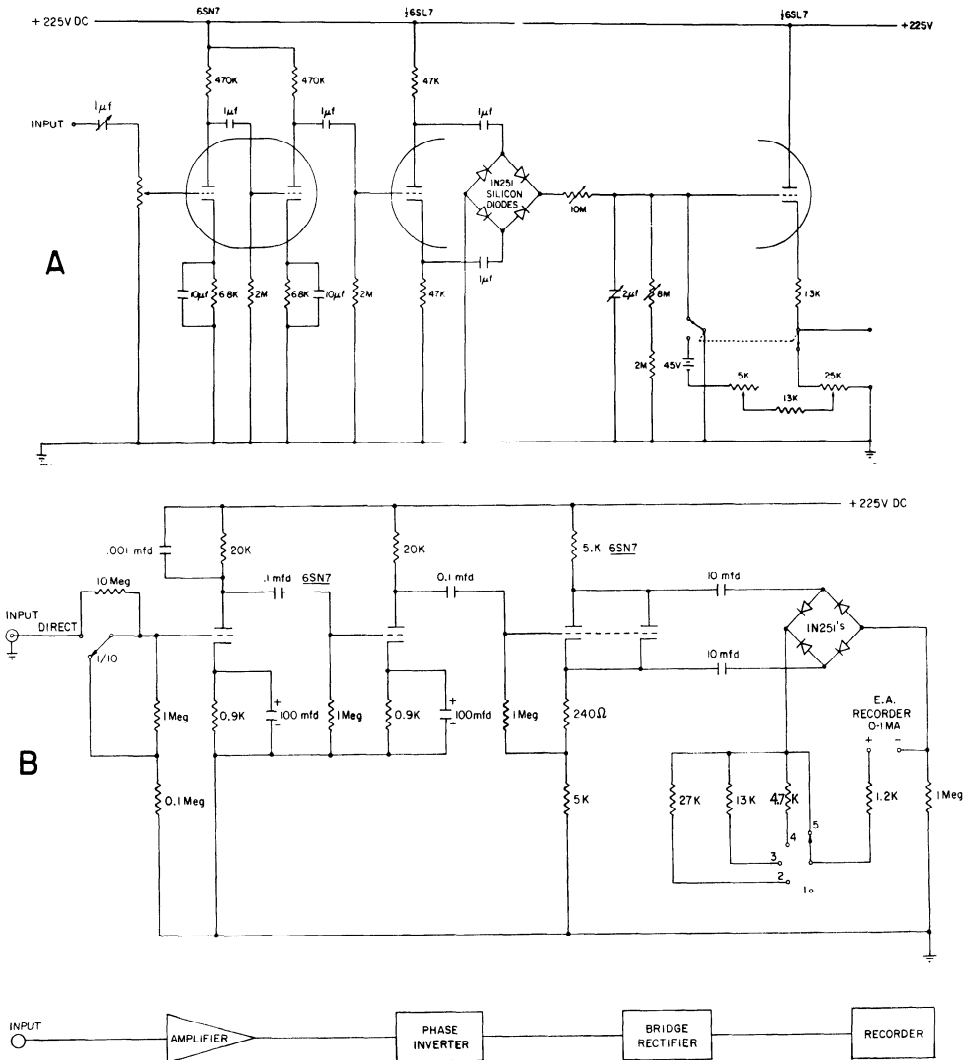


FIG. 1. Summator circuits. A: modified from Biedler (3); B: new, more versatile design by Tasaki.

A broad-spectrum "white" noise, produced by a General Radio random-noise generator type 1390B was projected as a free-field stimulus from an inexpensive Cletron 6×9 in. radio speaker (giving only ± 0.75 db variation in sound pressure level within the range of movement of the cat's head). The speaker was mounted at the top of the chicken-wire cage about 30 in. above the cat's head. Frequency analysis of the sound as received in the vicinity of the cat's head is shown in Fig. 2. Sound pressure levels were continuously monitored by a General Radio sound level meter type 1551B, scale C, 0.1-20 kc. Background sound pressure level within the cage was approximately 50 db with respect to 0.0002 dynes/cm²; that of the white noise was about 35 db above background. Various durations of sound exposure were tested. Less than about 2 hours seemed to omit interesting changes; more than 2 hours seemed to yield relatively more redundancy. Different intensities of sound exposure were tested. Intensities less than about 70 db have less effect on electrical activity; intensities greater than 90 db run the risk of end organ damage; intensities of about 80-85 db yield prominent responses and end organ damage is not likely. The cats were sacrificed by an overdose of Nembutal. Electrolytic lesions were made at the tip of each pair of electrodes to deposit iron which was identified by the methods of Marshall (18). Frozen serial sections, 50 μ thick, were stained with cresyl violet and examined microscopically for electrode location. The middle ears were examined under a 40 power dissecting microscope to exclude animals with signs of ear infection.

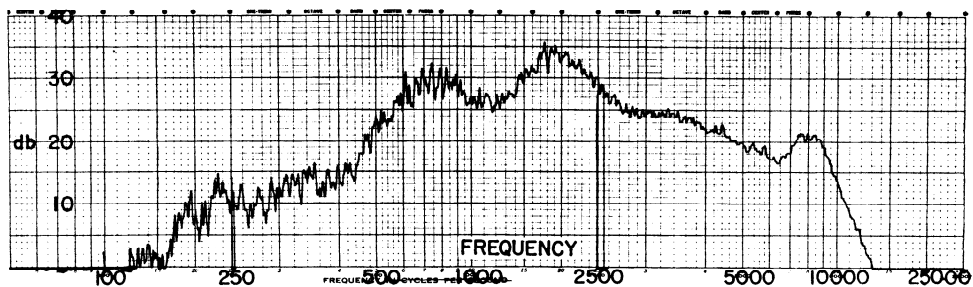


FIG. 2. Frequency response to white noise stimulation. Response recorded from vicinity of cat's head with General Radio sound level meter and analyzed by General Radio frequency analyzer. Relative scale set at 30 db for 1,500 cycles.

RESULTS

The level of summated "spontaneous activity" recorded from any given electrode pair in the absence of known experimental intervention remained approximately the same from day to day. Different electrode sites revealed spontaneous activities which were distinguishable by oscilloscopic inspection. The level of spontaneous activity was affected by the state of wakefulness or sleep and by bodily movement. During sleep, the level of summated activity recorded from sites above the pons rose (cerebral cortex, medial geniculate body, amygdala, hypothalamus, red nucleus, and midbrain reticular formation), whereas below the midbrain there was characteristically a decrease in the level of summated spontaneous activity (superior olive, trapezoid body, principal trigeminal nucleus, and cochlear nucleus). The level of spontaneous activity recorded from all sites tended to rise in association with bodily movements, the rise being greatest at the inferior colliculus and the lower brain-stem nuclei. There also occurred other fluctuations in the level of spontaneous activity which we have not been able to associate with any obvious changes in the environment or in the animals' comportment.

Generally the animals lay or sat quietly during the prestimulation period. At onset of white noise, the animals looked up at the loudspeaker and appeared attentive for several minutes before resuming quiet repose. A few cowered, or attempted to escape, but gradually became quiet and relaxed during the remainder of the experiment.

Effects of white noise stimulation

Typical effects elicited by white noise stimulation are presented in anatomical sequence along the classical auditory pathway from cochlea to cortex. Some variations in amplitude and pattern of summated response may be observed in the same animal during different experimental sessions. It is

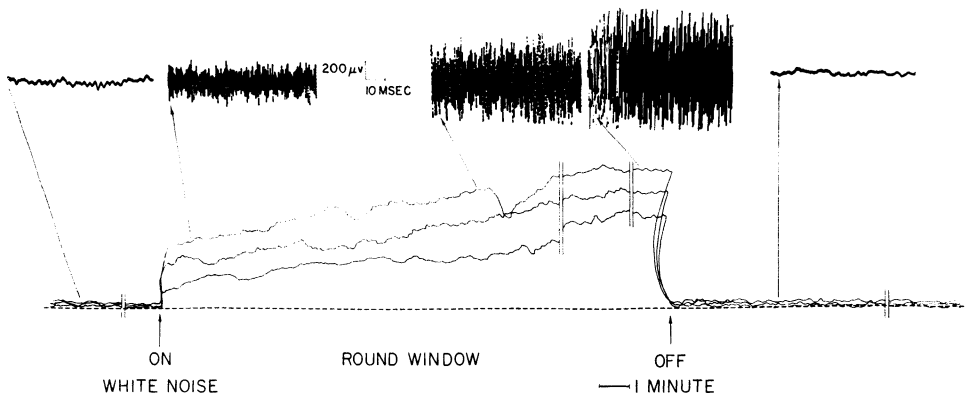


FIG. 3. Round-window responses. Three typical round-window responses before, during, and after 2 hours of steady white noise stimulation. In this and subsequent figures summator records are at bottom of figure, with control level of spontaneous activity prior to sound exposure indicated by interrupted horizontal lines. Parallel vertical bars through summator records indicate an interruption of representation of recording for periods of 50 min. Photographs of oscilloscopic responses from one of the animals, recorded at a much faster time scale, are related by arrows to particular moments during the summator record. Summator record time scale 1 min. Oscilloscope record time scale 10 msec.

our impression that behavioral studies will illuminate the nature of some of these variations.

Round window. (Fig. 3 shows results from three of four monopolar electrode placements.) The onset of noise was associated with a prompt increase in level of summated activity. The amplitude of this rise is logarithmically related to the sound pressure level of the stimulus in decibels (log/log straight line up to about 85 db). Continuing white noise exposure elicited a further very gradual response rise which reached a steady level after about $\frac{1}{2}$ hour of sound exposure. The final level recorded may be two to seven times greater than that observed shortly after onset of sound. Intermittently, during the total 2-hour sound exposure, transient marked decreases in response amplitude were imposed on this gradual rise. These transient decreases in amplitude were associated with bodily movements and vocalization. Discontinuation of the white noise was associated with a prompt return to the pre-exposure level.

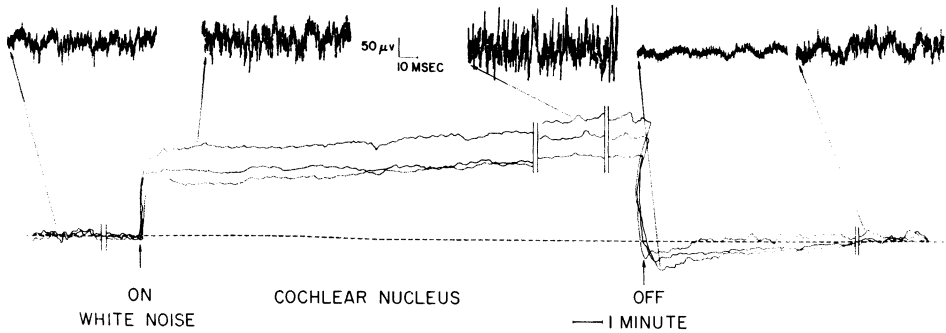


FIG. 4. Cochlear nucleus responses. Three typical cochlear nucleus responses before, during, and after 2 hours of steady white noise stimulation.

Cochlear nucleus. (Fig. 4 shows results from three of four bipolar electrode placements.) At onset of white noise there was an abrupt rise in summated activity but this was only about one-tenth the amplitude of the rise at onset at the round window. This response, like that at the cochlea, continued a further gradual rise with continuing sound stimulation. The gradual rise lasted from $\frac{1}{2}$ hour to 1 hour and amounted to half again the level shortly after onset. Movement and vocalization were associated with diminutions in response similar to those observed at the round window. At the cochlear nucleus, however, discontinuation of sound stimulation was associated with an abrupt fall in activity below the pre-exposure level. This aftereffect lasted from 30 sec. to 10 min. before gradually returning to control amplitude.

In three additional animals, bipolar electrodes intended for cochlear nucleus lodged among eighth-nerve fibers passing between the cochlear nucleus and restiform body. Response patterns recorded from these loci were the same as those from the cochlear nucleus except that there was no evidence for aftereffects. The amplitude simply returned to pre-exposure levels.

Superior olive. (Fig. 5 shows results from all three bipolar electrode placements.) Onset was associated with a smaller rise than at the cochlear nucleus. Continuing sound exposure was associated with a similar gradual rise, and movement and vocalization similarly attenuated the response amplitude. Following discontinuation of the sound, summated responses

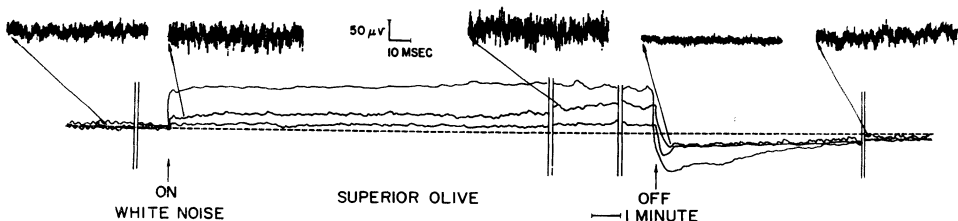


FIG. 5. Superior olive responses. Three typical superior olive responses before, during, and after 2 hours of steady white noise stimulation.

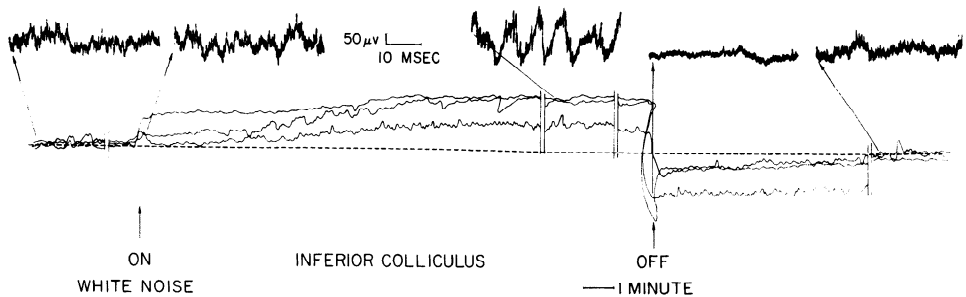


FIG. 6. Inferior colliculus responses. Three typical inferior colliculus responses before, during, and after 2 hours of steady white noise stimulation.

dropped substantially below control, returning to pre-exposure levels only after about 20-30 min.

Three additional bipolar electrodes located among fibers of the trapezoid body showed a somewhat larger initial onset rise and a shorter period of reduced activity following discontinuation of sound.

Inferior colliculus. (Fig. 6 shows all three bipolar electrode placements.) Rise at onset was less than at the lower auditory stations, about half or less than that at the cochlear nucleus. Following this, in two of the three sites, there was a decrease in amplitude before the appearance of a gradual rise during continuing sound stimulation. Movements and vocalization also attenuated response amplitudes. At discontinuation of stimulation, responses decreased below control levels. This aftereffect was of greater magnitude and duration than that at the lower stations. Its persistence was notably modified by the duration of sound stimulation: in one animal, periods of stimulation lasting 10 min., 2 hours, and 24 hours were associated with after-effects lasting 2 min., $\frac{1}{2}$ hour, and 6 hours, respectively.

Medial geniculate body. (Fig. 7 shows typical records from three of seven electrode placements.) Onset rise was very small and transient, returning to control level within less than 1 min., and remaining at or falling slightly below this level for the duration of the stimulation period. At discontinuation of sound, there was a further slight fall below control level which persisted for about 20 min. In medial geniculate body, fluctuations in activity associated with movement or vocalization were in the same direction (increase) before and during sound stimulation, in contrast with lower stations where activity increased before and decreased during sound stimulation. Fluctua-

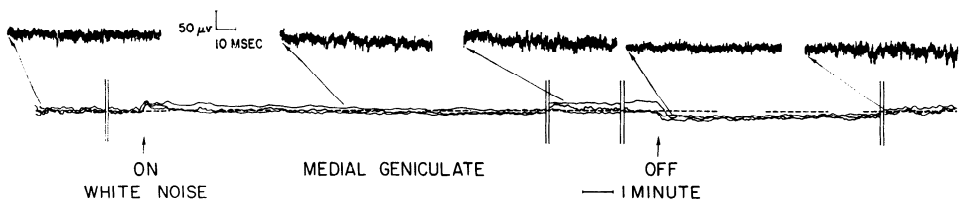


FIG. 7. Medial geniculate body responses. Three typical medial geniculate body responses before, during, and after 2 hours of steady white noise stimulation.

tions in spontaneous activity were three to four times greater in amplitude than were the effects of sound stimulation. Geniculate electrode emplacements were distributed within both rostral and caudal regions as well as in the magnocellular and parvocellular divisions of the nucleus. Among these placements the magnocellular region seemed to show slightly larger responses.

Two additional electrode pair placements within the brachium of the inferior colliculus showed essentially similar responses to those recorded from the medial geniculate body.

Auditory cortex. (Fig. 8 shows one of four typical response sites within the area encircled.) Cortical response to prolonged loud sound was limited to a small zone near the upper end of the posterior ectosylvian sulcus. At this

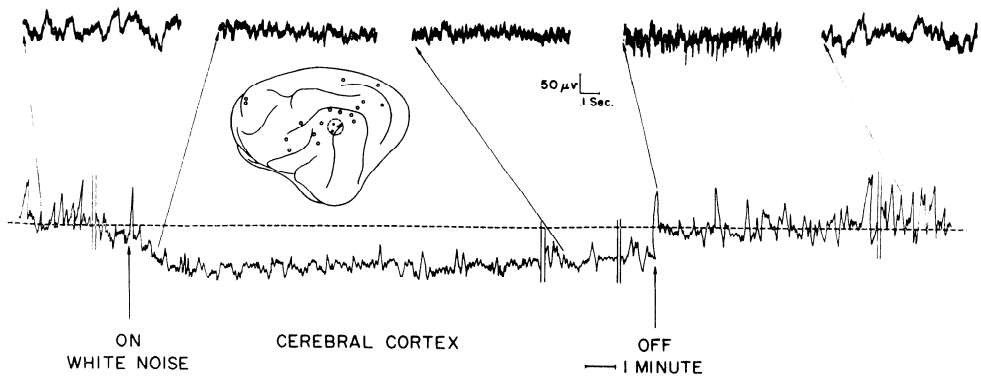


FIG. 8. Auditory cortex responses. Typical response recorded before, during, and after 2 hours of steady white noise stimulation, from the area encircled by dashed lines near tip of posterior ectosylvian sulcus in diagram of the cerebral cortex. Summator record time scale 1 min. Oscilloscope record time scale 100 msec.

location, onset of white noise was associated with a brief transient response rise followed by a fall below control level. The response reached a minimum by about 5 min. and remained low for the duration of stimulation. Both before and during sound exposure, movement and vocalization were associated with a rise in level of the record. The cortical response to sound was different from the response to nonacoustic arousal which consisted of a much smaller reduction in amplitude and which was widespread. Following discontinuation of sound stimulation, responses abruptly rose above and quickly returned to control level in two animals; in the other two there was simply a gradual rising return over a period of about 2 min. to control levels. Records obtained from bipolar electrodes located only a few millimeters from the upper end of the posterior ectosylvian sulcus did not show any sustained changes in recorded response during sound exposure other than those associated with simple arousal. This was equally true for electrodes still well within the so-called auditory cortex (the remainder of AI, all of AII and Ep).

Subcortical and cerebellar control sites. Onset of white noise was usually

associated with a transient rise in level of recording, but no sustained changes were observed during continuing sound exposure or at the end of stimulation. The only exceptions to this related to electrodes implanted close to the classical auditory pathway within the brain stem, in the principal trigeminal nucleus, ventral spinocerebellar tract near the superior olive, and within the restiform body between these two locations. At each of these sites, a small response occurring at onset of sound was sustained for the duration of sound exposure. At discontinuation of sound, responses returned directly to pre-exposure levels.

Anesthetized animals

Influence of anesthesia on spontaneous activity. Within a few minutes following intraperitoneal injection of Nembutal, spontaneous activity recorded from all subcortical electrode sites began to decrease in amplitude, reaching a steady level in about 30 min. Spontaneous activity fell to a greater extent if a larger dose of anesthetic was given. Cortical activity, in contrast, increased in amplitude during the first 15 min., remained elevated for 5-10 min., and then, as anesthesia deepened, declined to slightly below control levels. Increased cortical activity reappeared when the animals first began to emerge from anesthesia.

Influence of anesthesia on responses to white noise stimulation (Fig. 9). All stations along the classical auditory pathway showed a prompt rise in summated activity at onset of loud sound stimulation; however, the cortical response increase occurred only during the stage of anesthesia when cortical activity was elevated above control levels. During anesthesia, recordings from the auditory pathway below the inferior colliculus showed responses which were increased not only in relation to their anesthetized control levels, but also absolutely above the maximum amplitudes reached in the waking state. At the inferior colliculus, in the anesthetized state, the pre-stimulus control level was reduced considerably below that in the waking state; the rise at onset of sound was marked, but still below that achieved during sound stimulation in the waking state.

During the first few minutes following onset of sound stimulation, at all subcortical auditory stations, the initial onset peak was followed by a 10% decline over a period of 1 min. to a level which thereafter fell only slightly (1-2%) during continuing sound exposure. This is to be contrasted to the rising response obtained in waking animals during this same period. Termination of sound stimulation was associated with a return directly to pre-exposure level of spontaneous activity at the round window, inferior colliculus, medial geniculate body, and auditory cortex. At the cochlear nucleus and superior olive, poststimulatory responses fell below control levels and recovered gradually over a period of minutes. In effect, anesthesia obliterated the aftereffects seen in waking animals at the inferior colliculus and medial geniculate body, but left those at the lower stations apparently intact. Animals given irreversibly large doses of Nembutal still showed after-effects at the cochlear nucleus and superior olive.

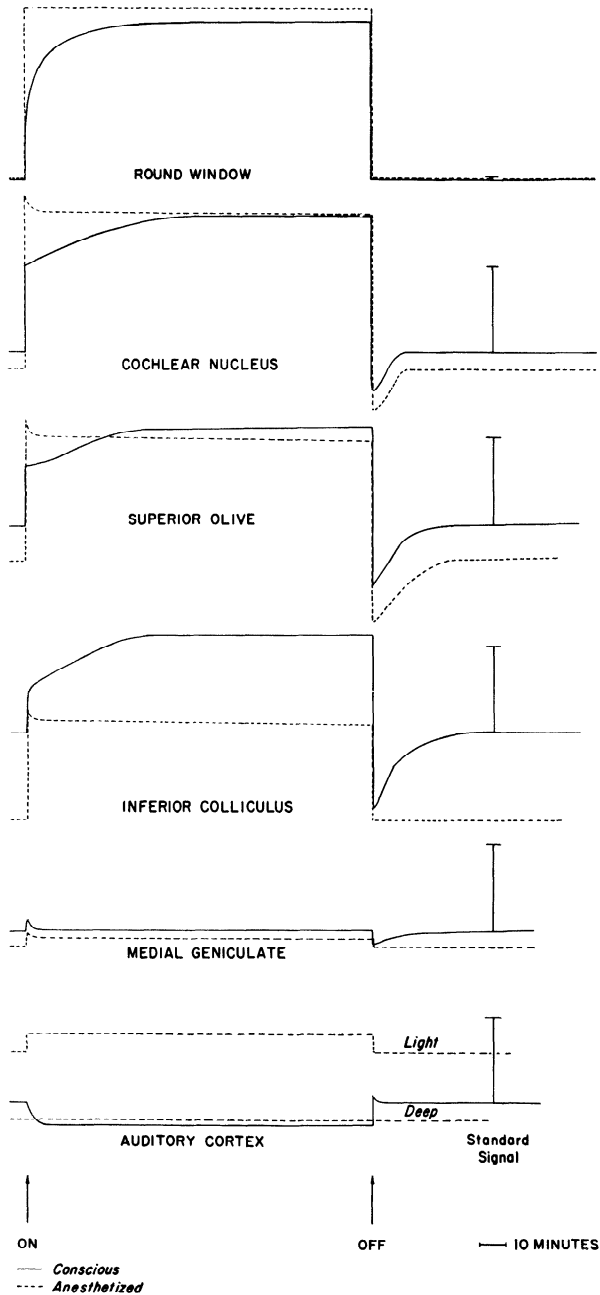


FIG. 9. Comparison between waking and anesthetized records. Schematic diagram illustrating typical records at each station from the same animal with and without Nembutal anesthesia. Continuous line refers to conscious state, interrupted line to anesthetized state. Two interrupted lines at cortex contrast effects of light anesthesia. (elevated record) with effects of deep anesthesia. Calibration by standard square wave (interval of pulse on = pulse off) $20\text{-}\mu\text{V}$. signal delivered to first-stage amplifiers. Time scale 10 min.

DISCUSSION

Localization of responses. In these experiments in waking animals, with neither reward nor punishment associated with loud, steady sound stimuli, responses in the form of sustained alterations in amplitude of averaged electrical activity were confined entirely to the classical auditory pathway. The only exception to this generalization concerned the margins of the brain stem immediately adjacent to the entrance of the auditory nerve.

Most studies of auditory mechanisms analyze responses to acoustic transients such as clicks and short tone bursts. These responses are so widespread in waking animals that some investigators have questioned what may constitute the proper auditory pathway (16). In the present experiments, for example, click-induced responses could be evoked from every electrode placement, including many locations remote from the classical auditory pathway. How does it happen that there is such a different map for sustained responses as compared with responses evoked by acoustic transients (including the onset of sustained sounds)? Perhaps the widespread responses relate not so much to the acoustic nature of the stimulus per se as they relate to change. Something of the same sort appears to occur with respect to the visual system: light flashes presented to waking animals elicit responses in regions far removed from the classical visual pathway (12).

We are inclined to believe that the nervous system may deal in special ways with environmental change in addition to specific sensory modalities. This interpretation implies that click- and flash-evoked responses may relate primarily to the characteristic of transiency and may not provide a proper designation for the extent of modality specific auditory and visual pathways. It raises the question as to whether the apparent confluence within the brain-stem reticular formation and cortical association areas of signals from separate sensory modalities may be primarily a confluence of signals pertaining to transients. In these experiments, stimulation through electrodes in the reticular formation induced alerting and looking around, a nonspecific arousal; stimulation of the medial geniculate body yielded a turning of head, eyes, and ears in the direction of the inactive loudspeaker over the cat's head from whence it had previously heard loud sounds.

Only a small cortical zone near the upper end of the posterior ectosylvian sulcus showed a sustained electrical shift of summated activity. This responsive zone was considerably smaller than that ordinarily depicted for auditory cortex and smaller than that which is attributed to individual frequency spectrums included in our stimulus. Gumnit (10) found a cortical d.-c. potential shift limited to this region, in response to short-duration tone stimuli, and Lilly and Cherry (15) showed that click-evoked activity begins here and is last to disappear from this region. Our results provide a third line of evidence indicating that this region has functionally unique properties.

Amplitude of responses. The background against which response amplitude changes are observed is the so-called spontaneous level of activity. In anesthetized animals, in the sound-attenuating room, severance of both

eighth nerves was followed by a marked reduction in ongoing activity at the cochlear nucleus and superior olive, but much less reduction at the inferior colliculus (manuscript in preparation). We infer that spontaneous activity at the cochlear nucleus and superior olive is more dependent on auditory input than is that at the inferior colliculus. This would account for the fact that in waking animals, at the onset of a given intensity of sound, there is a smaller rise above spontaneous control levels at the inferior colliculus than at lower stations. These findings reinforce the view (5, 25) that ongoing activity is not so much spontaneous as it is a reflection of interdependent relations among various parts of the nervous system, peripheral and central.

Are meaningful behavioral determinants extracted at lower stations, thereby reducing the amount of signalling engaging higher centers? Amplitudes of sustained responses to the same white noise are different in each region of the auditory pathway; they tend to decrease as one proceeds centrally (Fig. 10). At sound intensities used, round-window potentials are predominantly microphonic. The mechanisms of cochlear microphonics are thought to be different from those underlying electrical responses in nervous tissue; therefore, amplitudes of electrical response at the round window are not directly comparable to those recorded from the brain. Within the central nervous system there is a substantial decrement of response amplitudes along the succession of stations from cochlear nucleus to cortex. Katsuki and his colleagues (13), testing nonadapting single units along the auditory pathway during short-duration tone bursts delivered to unanesthetized cats, found that "the higher the level, the lower became the rate" of unit firing. Thus, with both gross and microelectrode recording methods there is less activity evoked at successively higher centers in response to a given sound stimulus. Something of the same sort appears to take place among single units of other ascending pathways (V. B. Mountcastle, personal communication). Evidence from ablation studies suggests that meaningful behavioral determinants may be extracted at lower stations. The discrimination of pitch and loudness is possible in the absence of higher parts of the auditory pathway which must be intact for correct sound localization and pattern discrimination (20).

Nevertheless, we must be cautious in interpreting biological significance in relation to relative differences in amplitude of electrical response. If the succession of lowered amplitudes going from cochlear nucleus to inferior colliculus means that the colliculus may be relatively less engaged in sensory evoked activity, what about the medial geniculate which shows no sustained response, and the cortex which shows a sustained reduction? In lightly anesthetized cats, however, all levels show a rise in sustained response. Is the medial geniculate body in the waking state "protected" from response to steady sound by some mechanism which is obliterated by anesthesia? Reduction of activity¹ at the cortex may be further evidence for inhibition

¹ By "activity" we mean all electrical responses recordable by these methods involving frequencies between 10 and 5,000 cycles/sec. We make no presuppositions as to the mechanism or site of origin of this activity beyond that it represents activity responsive to sounds,

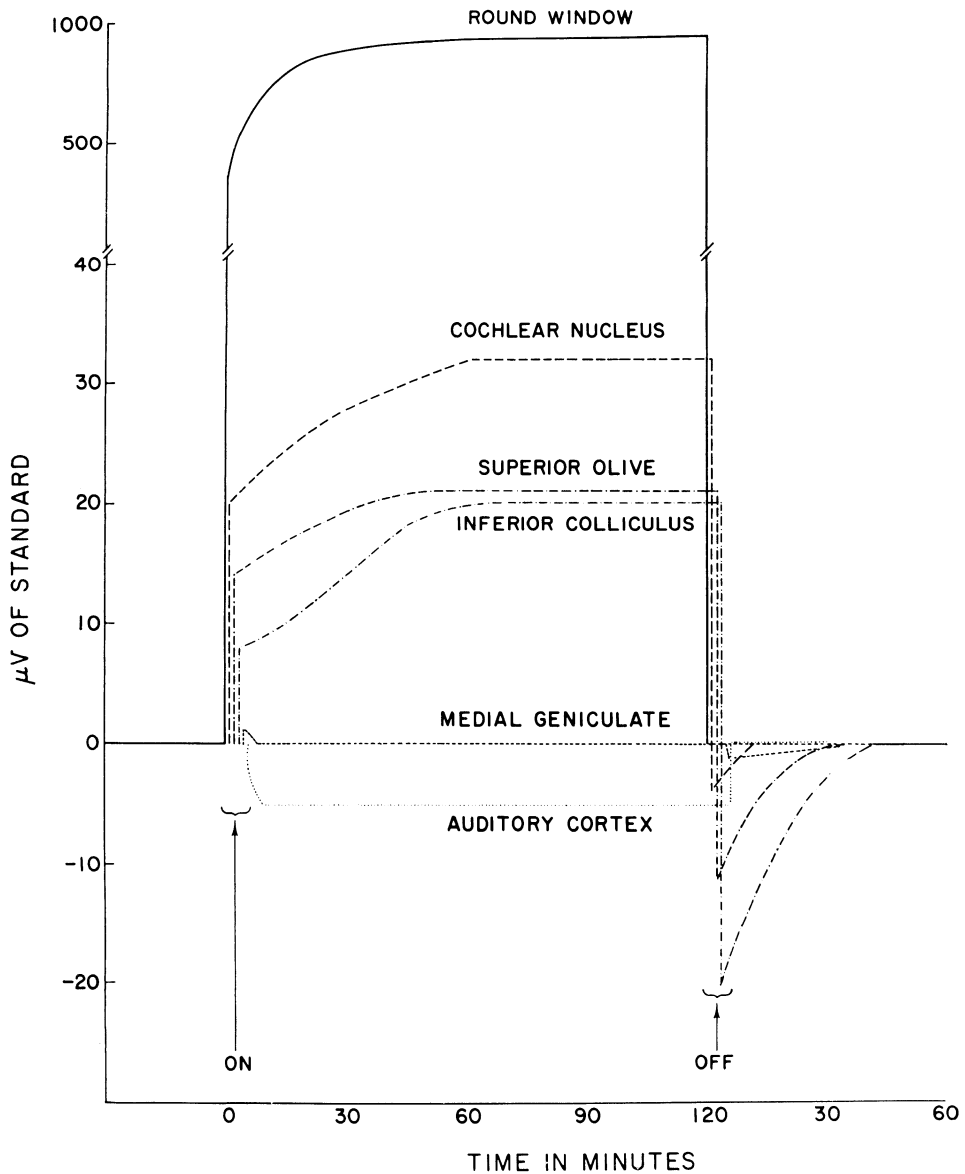


FIG. 10. Relative amplitudes of responses and aftereffects. Schematic diagram of typical responses in waking animals to illustrate relative amplitudes at different stations along the auditory pathway during and following steady sound stimulation. Relative comparison is made between amplitudes at onset, maximum amplitudes of response achieved, and magnitudes and durations of aftereffects. Amplitudes in μV . of standard calibrating signal (Fig. 9) are taken from the level of spontaneous activity at each region which is assumed to be zero. Note break in amplitude scale between 40 and 500 μV . Time scale in min.

anesthetics, etc. occurring nearby the electrodes. It is evident that the ratio of slow/fast waves increases as one ascends the auditory pathway but this would not account for the fact that long-duration sound in waking animals is associated with an over-all reduction in activity of the cortex.

affecting upper levels of the auditory pathway. The amplitude reduction at cortex is not an artifact of our system of recording. Frequency analyses which will be reported elsewhere (in preparation), indicate that at the medial geniculate body there is no change in frequency spectrum between spontaneous activity and activity recorded during sound stimulation. At the level of the cochlear nucleus and the inferior colliculus no change in frequencies below 250 cycles/sec. and an increase in all frequencies from 250 to 5,000 cycles/sec. occurred during sound stimulation in comparison with spontaneous activity. At the cortex there is a genuine reduction in amplitude of all frequencies between 10 and 250 cycles/sec., hence a genuine reduction in over-all electrical activity. The General Radio frequency analyzer employed is accurate to 10% between 10 and 20 cycles/sec. and accurate thereafter to 5,000 cycles/sec. to 2%. These data were collected in waking cats through the normal amplifying system.

Changing responses to unchanging stimulation. In conscious cats, long-continuing repetition of brief sensory stimuli (clicks or flashes), not associated with reward or punishment, may be followed by changes in amplitude of evoked response. These changes are interpreted to be an electrical representation of sensory adaptation or habituation. In the present experiments, responses to steady sounds show a slow, continuing rise in amplitude after the initial rise at onset, in all stations from round window to inferior colliculus. This rise has been shown by Carmel and Starr (6) to depend upon middle-ear-muscle action. Onset of loud sound induces an acoustic reflex contraction of both tympanic muscles which markedly attenuates amplitude of the response. During the next hour, the middle-ear muscles slowly relax, resulting in the gradually increasing electrical response. This reduction of tension in the middle-ear muscles is not due to fatigue inasmuch as the muscles can contract briskly and fully when the external auditory canal is touched, and when the intensity of the sound is abruptly increased or decreased. In addition, middle-ear-muscle contractions accompany general bodily movement of the animals and cause a transient marked attenuation of auditory responses, even when such movement occurs during the phase of gradual middle-ear-muscle relaxation. Carmel and Starr (6) identify this form of middle-ear-muscle contraction as nonacoustic in origin because it also occurs in totally deafened animals.

Nembutal anesthesia eliminates action of the middle-ear muscles. Under anesthesia, at all subcortical auditory stations, response at onset of sound develops a peak which decreases by about one-tenth of the onset amplitude during the next minute, and remains at approximately that level for the duration of sound exposure (Fig. 9). In unanesthetized animals following severance of the tendons of both middle-ear muscles, there is a similar response pattern during the first few minutes of sound stimulation, but thereafter responses at the cochlear nucleus and superior olive rise again gradually to approximately the onset amplitude. In these animals from which middle-ear-muscle action is precluded, both the onset peak and early decline and the rising response recorded from cochlear nucleus and superior olive must be due to the action of neural mechanisms alone.

Therefore, there are at least three separate dynamic mechanisms which may account for noncorrespondences obtaining between the unchanging environmental stimulus and the dynamic responses recorded along the auditory pathway: 1) acoustic reflexes involving the middle-ear muscles, 2) non-acoustic reflexes involving the middle-ear muscles, and 3) neural mechanisms acting alone.

Aftereffects. These experiments demonstrate that it is possible to induce aftereffects which last many minutes in several stations along the auditory pathway. The aftereffects involve a reduction in amplitude of electrical activity to below the level of prestimulatory control; the magnitude and duration of aftereffect being roughly related to the intensity and duration of stimulation. Microelectrode studies of units in the eighth nerve (7 and N. Y. S. Kiang, personal communication), cochlear nucleus (19, 22, 24), and trapezoid body (11), following a brief exposure to steady sounds, show a reversible decrease in rate of firing, as compared to the rate prior to such sound stimulation. Something comparable has been noted during observations in the olfactory (1), visual (2, 9), and somesthetic pathways (4, 14). There thus appears to be a general characteristic of sensory systems that units are reversibly reduced in activity for brief periods (from a few milliseconds to seconds) following brief periods of sensory stimulation (from a few seconds to a few minutes). Our evidence indicates that aftereffects can be observed over a vastly longer time scale.

Rawdon-Smith (21) measured altered auditory thresholds after monaural application of loud pure-tone stimuli to man. He found aftereffects not only in the stimulated ear but also in the unstimulated ear. Moreover, intervening visual stimuli restored the altered poststimulatory thresholds toward normal. These findings imply the operation of central mechanisms. Electrical aftereffects observed in the present experiments reveal central changes which might underlie perceptual phenomena.

The most general notion which would fit the phenomena of dynamic responses during and after steady stimulation in waking and anesthetized animals is that the nervous system actively resists being changed. Our evidence may be summarized as follows: *a*) spontaneous activity tended to be stable—activity at each station along the auditory pathway was remarkably constant from day to day over long periods; *b*) activity shifted only slowly in response to environmental change—at onset of noise, responses recorded from round window to inferior colliculus showed a prolonged lag before reaching to maximum amplitude; *c*) successively higher stations tended to be increasingly stable—they were in general less affected by environmental change; *d*) mechanisms responsible for stability may themselves be slow to change—aftereffects may result from persisting activity in mechanisms counteracting response to environmental change; *e*) these mechanisms involve active processes—anesthesia yields responses which correspond more closely to the stimulus.

Evidence for mechanisms inducing stability seems to conflict with evidence respecting adaptability of the nervous system. There is no conflict between these lines of evidence, however, providing appropriate time rela-

tions are taken into consideration. There is invariably a lag in adaptation which may be nothing other than an expression of this resistance to change.

SUMMARY

1. Conscious cats with multiple implanted electrodes were exposed to prolonged, steady white noise. Summated electrical activity was recorded before, during, and after exposure to the unchanging stimulation. By this means it was possible to examine the major stations along the auditory pathway in respect to their dynamic responses to a standard form of stimulation.

2. Whereas click responses could be obtained in many cortical and subcortical regions throughout the brain, responses to sustained sound stimulation were limited to the classical auditory pathway. Sustained cortical responses were localized to a small region near the upper end of the posterior ectosylvian sulcus, an area much smaller than that usually considered as auditory cortex.

3. Responses from lower auditory stations including the round window did not rise to maximum amplitude until after about an hour or longer of steady sound exposure. They were held in check by middle-ear muscle and central neural mechanisms which were both powerfully interfered with by barbiturate anesthesia.

4. Maximum sustained response amplitudes decreased as one proceeds from round window to cortex in the following approximate and relative proportions: round window 100, cochlear nucleus 3.5, superior olive 2.0, trapezoid body 2.1, inferior colliculus 1.8, brachium of the inferior colliculus ± 0.1 , medial geniculate body ± 0.1 , and cortex -0.6 .

5. Following discontinuation of prolonged, loud sound stimulation, every subcortical part of the central auditory pathway exhibited a profound, prolonged, reversible reduction in activity to below the level prior to sound stimulation.

6. All these phenomena of noncorrespondence between the sound stimulus and the response of the auditory pathway are interpreted as being due to active mechanisms resisting change. These electrophysiological phenomena may be related to perceptual effects and aftereffects associated with long-continuing sensory stimulation. Analysis of the effects of prolonged stimulation may provide experimental access to some of the mechanisms underlying memory, learning, and other phenomena relating to sensory experience.

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