EFFECT OF STIMULATION OF VISUAL CORTEX ON ACTIVITY OF SOMATOSENSORY CORTICAL NEURONS

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As indicated in a figure of LORENTE DE NÓ⁹⁾, thalamocortical projection fibers and intercortical association fibers converge on cortical neurons. Single unit analysis of interaction between different inputs in the cerebral cortex was repeatedly reported. It was demonstrated that stimulation of an unspecified thalamic nucleus had a facilitatory effect on unitary cortical sensory responses⁷⁾, that activity of the pyramidal cells was inhibited by an afferent volley from the nucleus ventralis lateralis³⁾, and that inhibition occurred through cortical interneurons⁸⁾. ASANUMA and OKAMOTO²⁾ showed that response elicited from pyramidal stimulation in motor area was depressed by stimulation of contralateral motor area. JUNG⁵⁾ described experiments on influence of different afferents upon neuronal activity of the visual cortex and suggested the convergence of specific retinal, nonspecific reticulothalamic and vestibular afferents.

BUSER and IMBERT⁴⁾, in the recent symposium on sensory communication, showed the responsiveness of single neurons from the "sensorimotor" cortex to different kinds of sensory stimulation-somatic, visual, and auditory and commented that the "motor" cortex is a polysensory area, having projections simultaneously from visual, auditory and somatic inputs, and the motor cortex behaves as a converging neuropile.

The present study concerns unit spike discharges recorded from the somatosensory cortex in response to electrical stimuli applied to the visual cortex and a contralateral sensory nerve. In some experiments, similar stimulation was applied to the visual and contralateral somatosensory cortex. It will be shown that occlusions occur between responses from different stimuli and associative volleys from the visual cortex modify the membrane potential of a somatosensory neuron and produce a change of response pattern of somatosensory activity in the cerebral cortex.

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METHODS

Thirty adult cats were anesthetized with chloralose (30 mg/kg). Since contraction of muscles still occurred after nerve stimulation, Flaxedil was subsequently injected into the femoral vein. Artificial respiration was maintained. The head was fixed in a stereotaxic instrument. Trephine holes, 10 mm in diameter, were made in the skull. The dura mater was removed for exposure of visual and somatosensory cortical areas. To minimize cortical movements, a lucite cup 5 mm in height was placed on the surface of the cortex. The bottom of the cup was formed by a celluloid plate with several 1-mm diameter pores. The cup fixed to a lucite bar and was filled with warm mineral oil. Through the pores in the celluloid plate the microelectrode was steered under stereomicroscopic vision and inserted into the cortex. Two silver wires with an interpolar distance of 1 mm were used to stimulate the surface of the posterior lateral gyrus, over which a circular dike of dental cement around the margin of the 10-mm diameter hole was filled with warm mineral oil. The superficial radial nerve was dissected, suspended by platinum wires, and stimulated with square-wave pulses of 0.5 to 1 msec duration, delivered through an R.F. isolation unit.

The recording microelectrode was a glass micropipette, drawn to an inside diameter of less than 1μ , and filled with 3M KCl. The d-c resistance was 20 to 50 megohms. The micropipette was inserted into the exposed cortex with a micromanipulator. The micromanipulator was poised over the headholder on a massive stand which was part of the stereotaxic instrument. A fine silver wire in the micropipette was connected to a grid of the push-pull cathode follower, and then through an r-c coupled preamplifier (time constant of 1 sec for FIG. 4 or 0.02 sec for FIGS. 1, 2, 3, 5, 6) to a cathode-ray oscilloscope. Another grid of the push-pull cathode follower was connected to the reference electrode attached to the skull of the animal.

Measurements on the depth of insertion of the microelectrode were made from the cortical surface as identified by the "pop" in the loudspeaker when the tip of the microelectrode made contact. The direction of insertion of the microelectrode was as nearly perpendicular to the cortical surface as possible. Electrodes were inserted slowly.

RESULTS

Stimulation of ipsilateral visual cortex. The neurons in the primary somatosensory cortex responded with a clustered pattern of firing to stimulation of the ipsilateral primary visual area. One to four spikes occurred most frequently in a population of responses following the stimulus. The range of latencies of discharges for the initial spikes in the response varied from 8 to 30 msec. One could not find spike discharges in the primary somatosensory cortex upon stimulating the contralateral primary visual area. These clusters of spike discharges were found at a level of 1.0 to 2.0 mm beneath the cortical surface.

Relation to strength of stimulation of the visual cortex was studied in experiments in which the spike discharge of cortical units followed stimulation of both the sensory nerve and the visual cortex. FIG. 1 shows that latencies of the response are shortened and number of spikes increased with increase in stimulation intensity. These units followed only lower rates of stimulation.

FIG. 1. Responses to stimulation of the ipsilateral visual cortex recorded from a somatosensory cortical neuron as increasing stimulus intensity in A, B, and C. Vertical calibration, 1 mv. Time scale, 1 msec.

Units activity appears, therefore, to be relayed over multisynaptic routes through association paths.

When the stimulation locus was moved 1.5 mm away from a stimulation site on surface of the visual area while setting microelectrode on a recording neuron, spike discharge disappeared and, if the stimulation electrode was put back in the original stimulated surface, the spike discharge reappeared, suggesting that the visual cortical area stimulated which caused a response in the somatosensory neuron, covered less than 1 mm² of the visual area at a stimulus parameter of 0.5 msec in duration and intensity of 7 volt of pulse.

Stimulation of the superficial radial nerve and interaction with volleys from the visual cortex. As previously stated, stimulation of the ipsilateral somatosensory cortex. About half the units which responded to stimulation of the contralateral radial nerve were driven also by ipsilateral primary visual area stimulation.

When the stimulation of the superficial radial nerve was preceded by stimulation of the visual cortex, the number of spike discharges to the shock was decreased providing that the stimulation interval was within about 40 msec; but beyond that interval no interaction was shown between two responses (FIG. 2). This demonstrates that the preceding cortical volley prevented the cortical neuron from being invaded by the sensory nerve volley, since the neuron had been under subnormal conditions following the first response. Likewise, if stimulation of the visual cortex was preceded by sensory nerve stimulation, the cortical stimulus failed to evoke a response if the stimulus interval was shorter than 50 msec (FIG. 3). The depression effect following the first stimulus was found often to last more than 100 msec. The cortical volley could not be considered as a pure inhibitory volley, for the cortical stimulus evoked spike discharges. It is possible, however, that after the cortical impulse had traveled

FIG. 2. Inhibitory effect of stimulation of the visual cortex on spike discharges of a somatosensory neuron evoked from a shock to the superficial radial nerve. Intensity of conditioning stimulation was increased from 1 to 4 in arbitrary units. Intensity of the test shock was constant. Vertical calibration, 1 mv. Time scale, 10 msec.

FIG. 3. Block of spike discharge elicited from stimulation upon the visual cortex, following stimulation of the superficial radial nerve. Stimulus intervals are 55 msec at 1; 41 msec at 2; 25 msec at 3. Intensity of conditioning and test shocks was constant. Vertical calibration, 1 mv. Time scale, 10 msec.

through, it left depression in excitability of the interneuronal path which became unresponsive to subsequent impulses.

Intracellular recording had characteristics of change in a neuronal membrane potential in the course of the process of interaction. FIG. 4 illustrates hyperpolarized afterpotential following a burst of spike discharges of a somatosensory neuron from stimulation of the superficial radial nerve. Amplitude of the postsynaptic potential elicited from stimulation of the visual cortex was decreased in a graded process as the interval of stimulation of the sensory nerve and the visual cortex was shortened. At about 130 msec of the stimulus interval, postsynaptic potentials summated to critical firing level from stimulation of the visual cortex, and spikes were generated following hyperpolarized afterpotential. By altering the volley interval, it is possible to measure this critical depolarization; e.g., it was 10 mv in FIG. 4.

One could find two groups of neurons responding to both cortical and sensory nerve stimulation: the first, those showing mutual inhibition, as previously described; the second, those showing temporal summation, as in FIG. 5. This figure demonstrates that two clusters of spikes, elicited from stimulation of the visual cortex and the radial nerve, had no interaction on each other and summated as additive number of spikes, there was one exception: number of spikes was the same as one of each response in the case of simultaneous incoming volleys from the visual cortex and the sensory nerve (FIG. 5C).

Interaction between responses to single shocks to ipsilateral visual and contralateral somatosensory areas. It was found that some cortical units responded to stimulation of both the ipsilateral visual and contralateral somatosensory areas. FIG. 6 demonstrates the interplay between these responses. A train of spikes elicited from a single stimulation of the visual area (FIG. 6A) was partially inhibited by weak stimulation of the contralateral somatosensory area, at a stimulus interval in 200 msec (FIG. 6B), and completely inhibited by strong stimulus (FIG. 6C). Likewise, if the stimulation of homologous contralateral somatosensory area was preceded by a volley from the visual cortex, the transhemispheric response failed to be evoked if stimulus interval was short (FIG. 6E). Thus it was demonstrated that the intercortical and transhemispheric spikes had a mutual blocking effect each other in the somatosensory cortex.

Site of interaction. A question arises in regard to the response elicited from stimulation of the ipsilateral visual cortex: whether association volleys travel through intercortical paths directly or via subcortical relays. In cats paralyzed with Flaxedil, we cut thalamocortical connections by sectioning horizontally at 10 mm depth below the surface of gyrus lateralis shown in FIG. 7. Unitary discharges in the somatosensory cortex could be recorded following the ipsilateral visual cortex stimulation. Thus nerve impulses can run from the visual cortex to the somatosensory cortex via association fibers in white matter of the neocortex. Interaction between responses to the cortico-cortical and sensory

FIG. 4. Intracellular record of blocking of spike discharges from stimulation of the visual cortex by conditioning sensory nerve stimulation. Stimulus interval was changed. Spike discharges from a shock to the visual cortex were elicited at about 130 msec after onset of response from the sensory nerve stimulation. Vertical calibration, 10 mv. Time scale, 10 msec.

FIG. 5. Temporal summation of responses from stimulation to the visual cortex and the superficial radial nerve. A: cortical stimulation preceded that of the sensory nerve by 35 msec. B: cortical and sensory nerve stimulations were delivered at the same time. C, D: sensory nerve stimulation was followed by cortical stimulation in 6 and 26 msec, respectively. Vertical calibration, 1 mv. Time scale, 10 msec.

volleys may occur even at the cortical level. FIG. 7 shows the brain of a typical experiment in which the entire lateral gyrus and the dorsal portion of the posterolateral gyrus were isolated by a subcortical section.

FIG. 6. Interactions between responses in the somatosensory cortex to stimulation of the visual area (V) and the contralateral somatosensory area (C). A: stimulation of the visual cortex only. B: contralateral somatosensory stimulation preceded the visual cortex stimulation. C: stronger stimulation of contralateral somatosensory area blocked response from stimulation of the visual cortex. C-E: Sequence of visual cortex and contralateral somatosensory stimulation reversed. Reciprocal inhibition appeared. Vertical calibration, 1 mv. Time scale, 10 msec.

FIG. 7. Black line shows incision to medial surface of the cortex at 10 mm beneath surface of the gyrus lateralis S: stimulated site of the gyrus lateralis posterior: for details see text.

DISCUSSION

Single unit analysis have been performed on convergence in the neocortex from different inputs. Associative cortical areas as well as primary projection areas in the cerebral cortex have been reported as convergent neuron pools in which facilitation and occlusion occurred between responses from different afferents. These are demonstrated in the visual cortex⁵⁾, motor cortex^{1,2,3,7,8)}, the suprasylvian gyrus⁶⁾.

Our results showed that occlusion and temporal summation elicited in the somatosensory cortex by following stimulation of somatic afferent and the visual cortex or contralateral somatosensory and ipsilateral visual cortex.

The question arises, what pathways are concerning in the projections to the sensorimotor cortex from the visual cortex. In our experiments responses in the somatosensory neuron from stimulation of visual area were still demonstrated after cutting connection between the visual cortex and subcortical structures. So intercortical pathway may contribute to results. It is, however, possible to consider the pathway through subcortical nucleus for the interaction. Associative nucleus in the thalamus, e.g. the thalamic reticular nucleus, is working. The primary somatic nucleus in the thalamus, however, could not be detected as location of interaction between responses from stimulation of the primary visual cortex and the radial nerve. (unpublished data) As seen in FIG. 4 a somatosensory neuron receives synaptic bombardment by nerve impulses from the visual cortex. With increasing intensity of stimulation of the visual cortex, the number of excitatory synapse in a somatosensory neuron activated to association volleys was increased, and excitatory postsynaptic potentials were summated spacially or temporally and initiated spike discharges when the potential reached the critical level (FIG. 4). The hyperpolarized afterpotential following the response had a depressive effect on occurrence of spike discharges thereafter. Stronger stimulation produced longer hyperpolarized afterpotentials which had longer depressive effect (FIGS. 2 and 4). This situation took place also when sensory volleys preceded association volleys. Recurrent inhibition could be considered in the neuron having long depression period.

In the case of temporal summation (FIG. 5), the inhibitory effect may be lacking. When associative and sensory volleys arrived somatosensory neuron coincidentally summative postsynaptic potentials reach a critical firing level and bursts of spikes, the number of which is the same as in the case of sensory nerve stimulation (FIG. 5C), fire.

It may be suggested that the membrane potential of a somatosensory cortical neuron is caused to fluctuate not only by the characteristics of the cell membrane, but also by synaptic bombardment at a subcritical level, through association paths from other cortical areas; therefore the excitatory state of the neuron is modified.

LATIMER and KENNEDY⁶⁾ studied unit activity in the suprasylvian cortex following stimulation of contralateral homologous cortical area, electrical stimulation of foodpads, flashes of light and audible clicks; the neurons frequently responded to both a transcallosal volley and peripheral stimulation, suggesting that the callosal and various other inputs may converge on the same cells. The present work also suggests that cortical neurons in the somatosensory cortex are converged upon by thalamocortical, ipsilateral corticocortical, and transhemispheric paths.

JUNG⁵⁾ suggested that the primary visual cortex is not merely a primary projection area, but also a site of coordination, because of the convergence on the visual neurons from different inputs and their interaction. Even the primary sensorimotor cortex is an integration system of various afferents as shown in the present investigation.

It may be considered that antidromic volleys from the visual cortex elicited blocking effect on responses from somatic volleys in the case of using electric shock on the cortical surface. We could find postsynaptic potentials (FIG. 4) and multiple spikes following a single shock on the visual cortex in the somatosensory cortex. So we may say that orthodromic volleys come in the somatic cortex and influence to activity of somatic neurons through the inter-cortical pathways.

As BUSER and IMBERT mentioned, the somatosensory cortex must be considered functionally as site for sensory motor integration because of convergence from somatic, visual and auditory inputs and relation to motor system. We did not confirm whether responsive neurons are contained pyramidal motor system.

Our conclusion supports the suggestion by BUSER and IMBERT that somatomotor cortex is integrative locus.

SUMMARY

Interaction between responses elicited in the somatosensory cerebral cortex, following single shock stimulation of the visual cerebral area and the superficial radial nerve or the contralateral somatosensory area, was studied in cats anesthetized with chloralose and immobilized with Faxedil. The range of latencies of discharges for the initial spikes from stimulation of the primary visual cortex varied from 8 to 30 msec in the somatosensory cortex. Spike discharges, recorded from a single cortical neuron, were reciprocally interacted by a conditioning-testing procedure and were blocked by a preceding response in some neurons; in other neurons, temporal summation was shown. The depressive effect following the first stimulus was found often to last more than 100 msec. Blocking of spike discharges following stimulation of the visual cortex was produced by the hyperpolarized afterpotential in the response elicited

from stimulation of the sensory nerve. These results suggest that associative volleys from another cortical area modify activity of the somatosensory cortical neuron as depression or temporal summation.

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