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Responses of cat's dorsal hippocampal neurones to moving visual stimuli

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Abstract. Response properties of visually driven neurones in the cat's hippocampal region were investigated. Out of 688 single cells observed 181 (26%) were visually driven. Ocular dominance was determined for 147 of those cells, 90 of which were driven only by the contralateral eye, 20 were driven exclusively by ipsilateral eye and 37 neurones could be activated by both eyes. Receptive field boundaries were outlined for 157; 152 of those neurones were movement-sensitive, and 125 neurones were sensitive to stationary stimuli. A small group of neurones (13%) showed more pronounced reactions to the vertical direction of motion. Some neurones (22%) revealed sensitivity to the shape and size of the applied visual stimuli. These results confirmed earlier data indicating that visually driven neurones in hippocampal region possess complex properties. They are probably involved in a higher level of visual information processing.

Key words: hippocampal neurones, visual receptive fields, direction sensitivity, orientation sensitivity, ocular dominance

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INTRODUCTION

The results of a number of investigations indicate that neurones in the hippocampal region showed well defined sensitivity to the sensory stimulation (Green and Machne 1955, Vinogradova 1965, MacLean et al.1968, Brajnik and Vinogradova 1974, Gloveli and Ioseliani 1981, Harutiunian-Kozak et al. 1985, Kazarian et al. 1991). It was also shown that some neurones in hippocampal regions CA_1 and CA_3 are involved in the central processing of visual information (Gloveli and Ioseliani 1981, Harutiunian-Kozak et al. 1985, Kazarian et al. 1991). The receptive fields of hippocampal neurones have well-defined boundaries and stimulation by stationary and moving visual stimuli could elicit different reactions in those cells. Thus, the dorsal hippocampus, an important structure of the limbic system, is engaged in the processing of the incoming visual information. These data fit well with the concept of the important role of the limbic system in the processes of memory and learning (MacLean et al 1968, MacLean and Creswell 1970, O'Keefe and Dostrowski 1971, O'Keefe and Nadel 1978, Oniani 1980, Olton 1983, Heit et al.1988, Squire 1992, Shen et al.1994). Nevertheless, until now the investigations concerning the organization of sensory inputs to the cat's limbic system based on a detailed analysis of single unit activity are relatively rare (MacLean et al. 1968, MacLean and Creswell 1970, Gloveli and Ioseliani 1981). Thus the problem of functional organization of visual sensory input to the cat's dorsal hippocampus still needs further exploration.

The present study is the continuation of earlier investigations (Harutiunian-Kozak et al.1980, Harutiunian-Kozak et al. 1985) concerning the properties of visually driven single neurones in the cat's dorsal hippocampus.

METHODS

The experiments were conducted on cats weighing 2.5-3.5 kg. Cats were anaesthetized with ether for the initial surgery. Tracheotomy and cannulation of the femoral artery and a subsequent brainstem pretrigeminal transection (Żernicki 1986) were performed under deep anaesthesia. The transection eliminated pain and anaesthesia was subsequently discontinued. The animal's head was fixed in a stereotaxic apparatus (Horsley-Clarke, modified for visual research). A window in the skull overlying the left dorsal hippocampal region was trepanated and filled with soft wax to avoid brain pulsation. Intramuscular injection of the myorelaxant Ditilin (diiodide dicholine ester of succinic acid), 7 mg/kg, immobilized the animal which was then maintained with artificial ventilation (19 strokes/min, stroke volume 20 ml/kg body weight). Body temperature was kept at 38°C with a heating pad. Pupils were dilated with a topical application of 0.1% Atropine solution and corneas were protected from drying with zero power contact lenses. Nictitating membranes were retracted by instillation of 1% Neosynephrine into the conjunctival sac. Additional spectacle lenses were used for optimal focusing of the eyes on the screen. Arterial blood pressure was continuously measured and remained at 90-100 mm Hg. The heart activity and EEG were constantly monitored.

Single unit activity was recorded 2-3 h after the cessation of the ether anaesthesia. Tungsten microelectrodes (Hubel 1957) covered with vinyl varnish with a bare tip of 2-5 μm were used. Single unit activity was recorded with conventional methods and analysed with ANOPS - 101 analyser, using the poststimulus time histogram mode. We used a 2 s time base and 4 ms bin width. Averaging was achieved by repeating the same stimulus 16 times and adding the responses. Direction sensitivity index was calculated from the histograms acording to the equation $D = 100\ [1-(Rnp/Rp)]$. Rnp and Rp are the strengths of responses in imp/s taken from PSTH for nonpreferred and preferred direction respectively. Directionally sensitive cells were defined as those with a DS-index between 100 and 20, and those with a DS-index between 19 and 0 were defined as direction non-sensitive cells.

The receptive fields of neurones were plotted on a 90° white concave screen that could swing, thus

covering 180° of the visual angle. It was situated in front of the animal at a distance of 1 m from the nodal points of the cat's eyes. Position of the Area centralis on the screen was plotted with the method of Fernald and Chase (1974).

Stimulation was performed with moving bright and dark bars and spots of different sizes. In some experiments moving edges were used, because the neurones reacted optimally to this type of visual stimulation. The angular velocity of moving stimuli was 40°/s, which was optimal for most hippocampal neurones.The values of contrast for the bright and dark stimuli against the background were kept constant in all experiments. The luminance of the bright stimuli was 8 lx against the 2 lx background and dark stimuli had conversely 2 lx luminance against 8 lx background. The reflective index of the screen was 0.85 and therefore the ambient illumination was kept in the mesopic range. This helped to maintain a constant contrast sensitivity of the cells. The motion of stimuli was achieved with a galvanometer system controlled by a trapezoidal waveform generator.

Coagulation was performed at the successful recording points (10 mA for 5 s). The brain was perfused with physiological saline followed by 10% formaline solution. The localization of the recording site was defined on 40 μm histological sections.

RESULTS

Our previous results showed that there were no essential differences in the properties of cell responses and visual receptive field organization between the CA_1 and CA_3 hippocampal areas (Kazarian et al. 1991). We have not observed any specific neuronal organizations in different parts and layers of dorsal hippocampus relative to their response patterns. Thus the data presented here comprise all the neurones investigated in both areas CA_1 and CA_3. Altogether 712 electrode penetrations were made in the hippocampal region. Swish reactions (multineuronal responses) to visual stimulation were observed during 281 penetrations, whereas there were no such reactions observed during the remaining penetrations. Among 688 single cells picked up by microelectrodes only 181 (26%) neurones were visually driven. The receptive field boundaries of neurones were determined for 157 cells. For 24 neurones the receptive field borders were not determined because of weak reactions to visual stimuli and habituation to the stimuli applied; after one or two presentations of the stimulus responses of such cells disappeared and this did not allow us to delimate their receptive fields. The majority of these neurones (129 of 157) showed a moderate level of spontaneous activity (5-10/s) and 28 neurones had no spontaneous discharges. The ocular dominance was measured for 147 neurones and the results showed that the majority of visually driven neurones were driven by the contralateral eye (90 out of 147), 20 neurones were driven by the ipsilateral eye and 37 were activated by both eyes.

Generally, all visually driven neurones in the hippocampal region were sensitive to moving visual stimuli and only 5 of 157 did not respond to the stimulus motion. Stationary visual stimuli were less effective and 32 neurones out of 157 did not respond to the flashing light spot located within the receptive field. Of 152 movement sensitive neurones 105 were direction non-sensitive and 47 were found to be direction sensitive (Ds index above 20) i.e. they had asymmetrical responses to the two opposite directions of movement, displaying preference for one direction and absence of responses, or diminution of spikes to the opposite direction of motion. A comparison of responses to the motion of stimuli along vertical and horizontal axis of the receptive fields revealed that some neurones (16 out of 152) showed a stronger reaction to vertical movement as compared to horizontal movement. Only 2 neurones reacted more intensely to horizontal movement. Figure 1 shows responses of one of the orientation sensitive neurones to the horizontal (Fig. 1A-D) and vertical (Fig. 1E-H) movements of the visual stimuli (light and dark spots and bars) across the vertical and horizontal axes of the receptive field respectively. The optimal responses of the neurone presented in Fig. 1 were elicited by 9° spots and 15° x 4° bars. As is shown in the figure, the

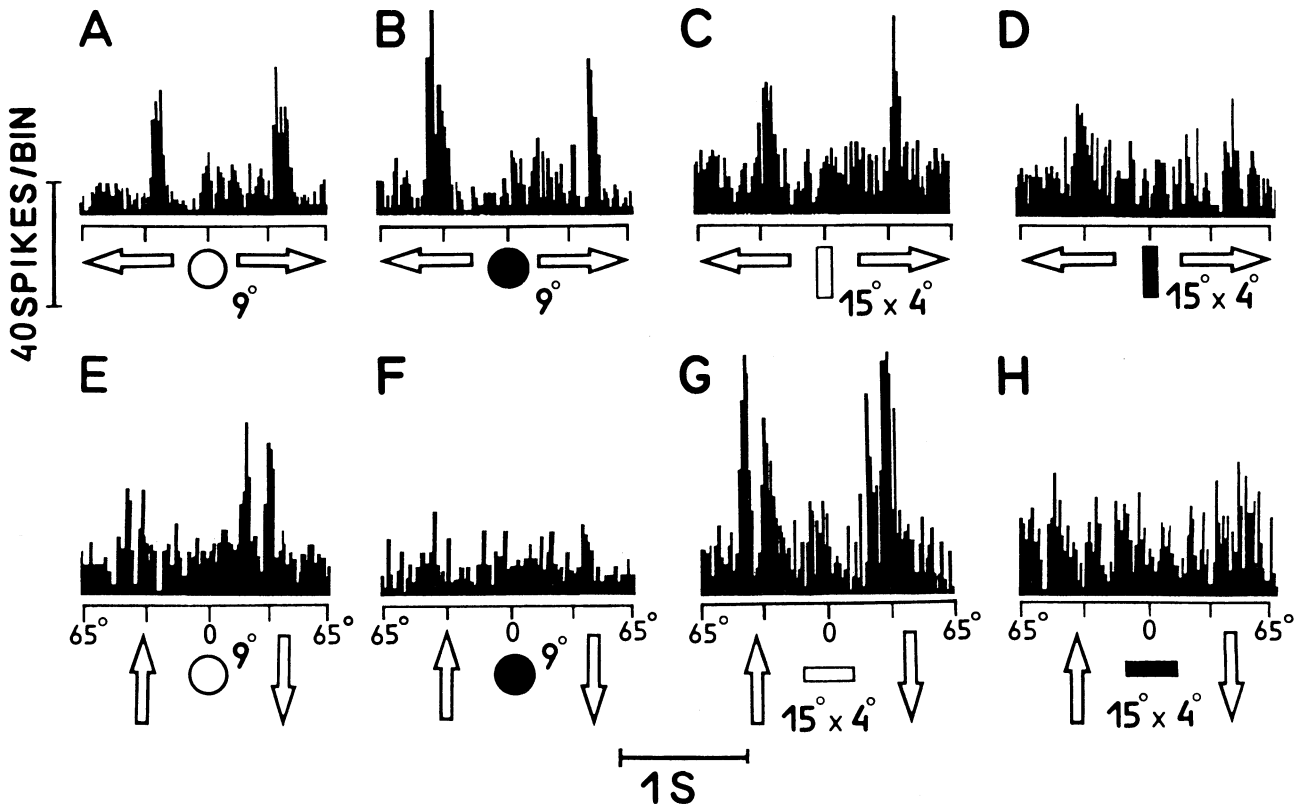

Fig. 1. Post-Stimulus Time Histograms (PSTH) of responses of a hippocampal neurone to the movement of spots and bars along the horizontal and vertical axes of the receptive field. Stimulus sizes are given in degrees of visual angle. A-D - cell responses to 9^{o} moving light (A) and dark (B) spots and 15^{o} x 4^{o} light (C) and dark (D) bars across the horizontal axis of the receptive field. E-H, responses of the same neurone to the movement of 9^{o} light (E) and dark (F) spots, light (G) and (H) 15^{o} x 4^{o} bars across the vertical axis of the receptive field. Ordinates: number of spikes per bin. Abscissae: time of stimulation (2 s). The arrows indicate the direction of motion. Average of 16 repetitions of stimulation. The explanations are the same for the subsequent figures.

movement of a light spot across horizontal axis of the receptive field evoked direction non-sensitive response of the cell with a slight preference of the left-to-right direction (Fig. 1A). A change of the movement direction to vertical resulted in a direction sensitive reaction of the cell with the preferred direction downward (Fig. 1E). The horizontal movement of a dark spot (Fig. 1B) elicited a clear-cut reaction of the cell to two opposite directions of motion with a preference of right-to-left direction (the opposite was true for the light spot), whereas the vertical movement of the same dark spot was not effective at all (Fig. 1F). Thus, the cell orientation sensitivity was better expressed for the dark spot, as compared to the light one. Fig. 1C, D, G and H presents the responses of the same neurone to the moving light and dark bars (15^{o} x 4^{o}). Changing the the shape of the stimulus brought some changes in response pattern of the cell. The responses to the light bar moving horizontally were weaker (Fig. 1C) than those evoked by the same stimulus moving vertically (Fig. 1G). The opposite results were registered when the moving light spot was used. Here the horizontal movements were more effective. The motion of a dark bar in a horizontal plane evoked weak responses (Fig.1D), and movement in the vertical plane evoked no response at all (Fig. 1H). Thus, the shape and contrast of visual stimuli seem to be important in determining orientation sensitivity of visually driven hippocampal neurones.

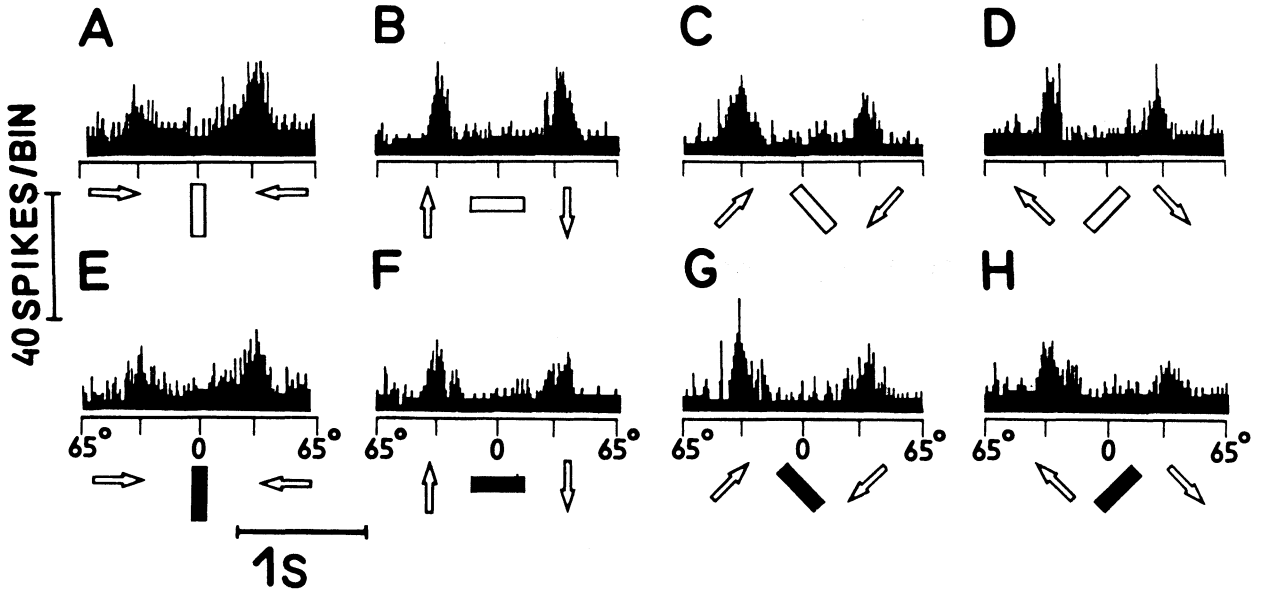

Fig. 2. PSTH of responses of a hippocampal neurone to light and dark bars moving in different orientations of motion. A, E, responses of the neurone to the movement of light (A) and dark (E) bars across the horizontal axis of the receptive field. B, F, responses of the same neurone to the movement of light (B) and dark (F) bars across the vertical axis of the receptive field. C, G, responses of the same neurone to the movement of the light (C) and dark (G) bars along the trajectory 45° oblique to the horizontal axes of the receptive field. D, H, responses of the same neurone to the movement of light (D) and dark (H) bars along the trajectory 135° oblique to the horizontal axis of the receptive field. The size of bars - 2° x 4° of visual angle.

Responses of another hippocampal neurone, which at first sight did not show marked changes depending on the orientation of the moving stimulus are presented in Fig. 2. However, further tests revealed differences in responses to different orientations of motion. For example, the neuronal responses illustrated in Fig. 2A and B were elicited by a light bar moving across the receptive field's horizontal and vertical axes (Fig. 2A and B) respectively. The cell reacted to the horizontal movement of the light bar by a directionally-sensitive response (Fig. 2A) with the preferred direction from right to left, whereas the vertical movement of the same bar elicited a direction non-sensitive response (Fig. 2B). Qualitatively similar responses were evoked by the dark bar moving horizontally (Fig. 2E) and vertically (Fig. 2F). Shifting the angle of motion to 45o against the horizontal axis of the receptive field revealed slight tendencies for directional sensitivity for 45° (Fig. 2C and G) and 135° oblique movements (Fig. 2D).

The hippocampal neurones (32 out of 152 neurones) revealed differences in their reactions to the different sizes of the applied visual stimuli. For example, responses of the neurone presented in Fig. 3 show a clear-cut reaction to the movement of a 2° dark spot (Fig. 3A) whereas the bright spot (2°) movement did not elicite any reaction of the cell (Fig. 3E). Larger sizes of the spots (7°) did not elicite any responses of the cell (Fig. 3B and F). The same neurone was tested also by moving dark and light bars (Fig. 3C, D, G and H). As is seen from the figure the responses of the cell are more accentuated to the presentation of 7° x 11° dark and light bars (Fig. 3D and H) in comparison with the responses to the movement of smaller bars 2° x 4° (Fig. 3C and G). Thus, the enlargment of the stimuli brought opposite effects for moving bars and spots.

In the next series of experiments the different velocities of motion were tested. Nearly half of the investigated neurones (48%) showed sensitivity to the velocity of motion and changed their response

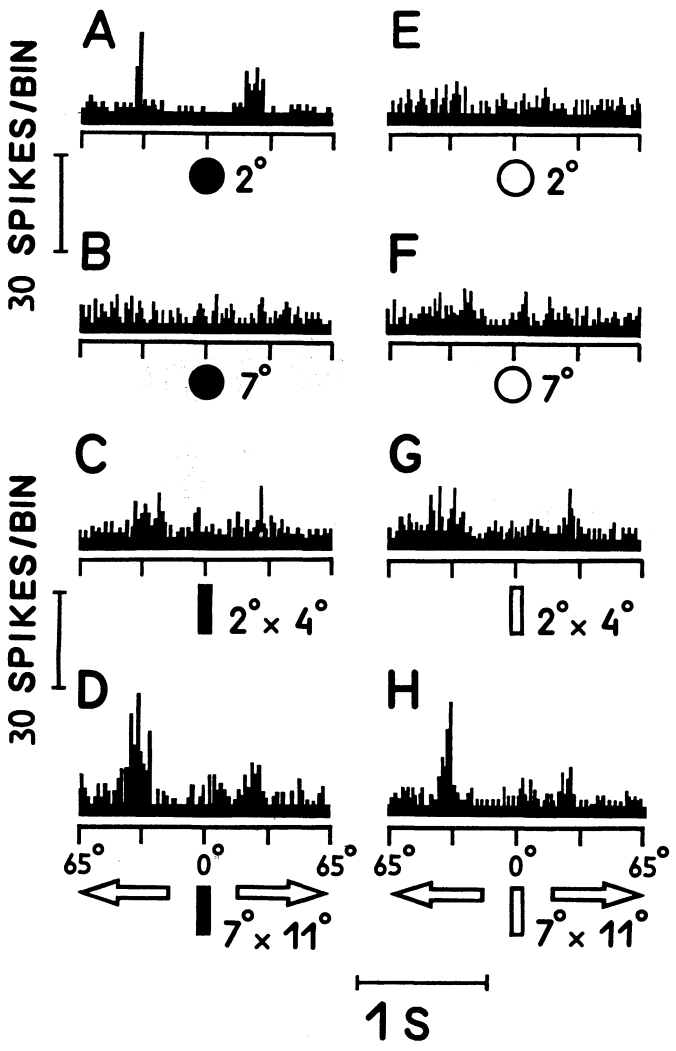

Fig. 3. PSTH of responses of a hippocampal neurone to the motion of light and dark spots and bars of different sizes across the horizontal axis of its receptive field. A, E, cell responses to the movement of 2° dark (A) and light (E) spots. B, F, responses to the movement of 7° dark (B) and light (F) spots. C, G, responses to the motion of 2° x 4° dark (C) and light (G) bars. D, H, responses to the movement of 7° x 11° dark (D) and light (H) bars.

patterns with the change of velocity of visual stimulus crossing their receptive fields. In Fig. 4 the responses of two hippocampal neurones of this type are presented. Both neurones responded optimally to the edge movement along the horizontal axis of their receptive fields, so this type of stimulus was chosen to test the effect of velocity changes. As is shown in the Fig. 4, the high (65°/s) velocity of movement of the edge elicits clear-cut direction-sensitive responses of the cell (Fig. 4A), whereas the slower (13°/s) motion elicited responses in the null direction as well and changed the preferred direction to the opposite one (Fig 4B). Further slowing of the velocity of the edge motion (6.5°/s) transformed the cell responses into the direction non-sensitive (Fig. 4C). Right-to-left direction of edge movement across the receptive field of the same cell when the edge motion from left to right lightened the receptive field, (Fig. 4D - F) elicited the same types of responses, although less accentuated. The next neurone presented on Fig. 4 showed optimal responses at the velocity of 13°/s (Fig. 4H) whereas the faster (Fig. 4G) and slower (Fig. 4I) movements elicited weaker responses. Thus, it seems that visually driven neurones in the hippocampus have, in addition to the orientation and contrast sensitivities show velocity-dependent reactions too.

Ocular dominance was tested on 147 visually driven hippocampal neurones. The majority (90) of the investigated neurones were contralaterally driven and 20 neurones were activated ipsilaterally. The neurones, which were activated by both eyes comprised a group of 37 neurones. The neuronal responses could have different patterns depending on the stimulated eye. Figure 5 shows the responses of a binocular neurone to the movement of light and dark spots and bars across the horizontal axes of the receptive field. The neurone showed negligible differences in responses to the movement of a 3° light spot presented to the contralateral eye (Fig. 5A), ipsilateral eye (Fig. 5B) or binocularly (Fig. 5C). A moving dark spot (3°) elicited direction-sensitive responses in the same cell (preferred direction from right to left) from both ipsilateral (Fig. 5D) and contralateral eyes (Fig. 5E), whereas binocular stimulation evoked responses in the null direction as well (Fig. 5F). Responses of the same neurone to the movement of the dark bar (2° x 4°) were similar to the responses elicited by the dark spot (Fig.5G-I). It seems thus, that the ocular dominance along with the contrast and velocity of visual stimuli influencs the overall pattern of responses of visually driven neurones in the hippocampal region.

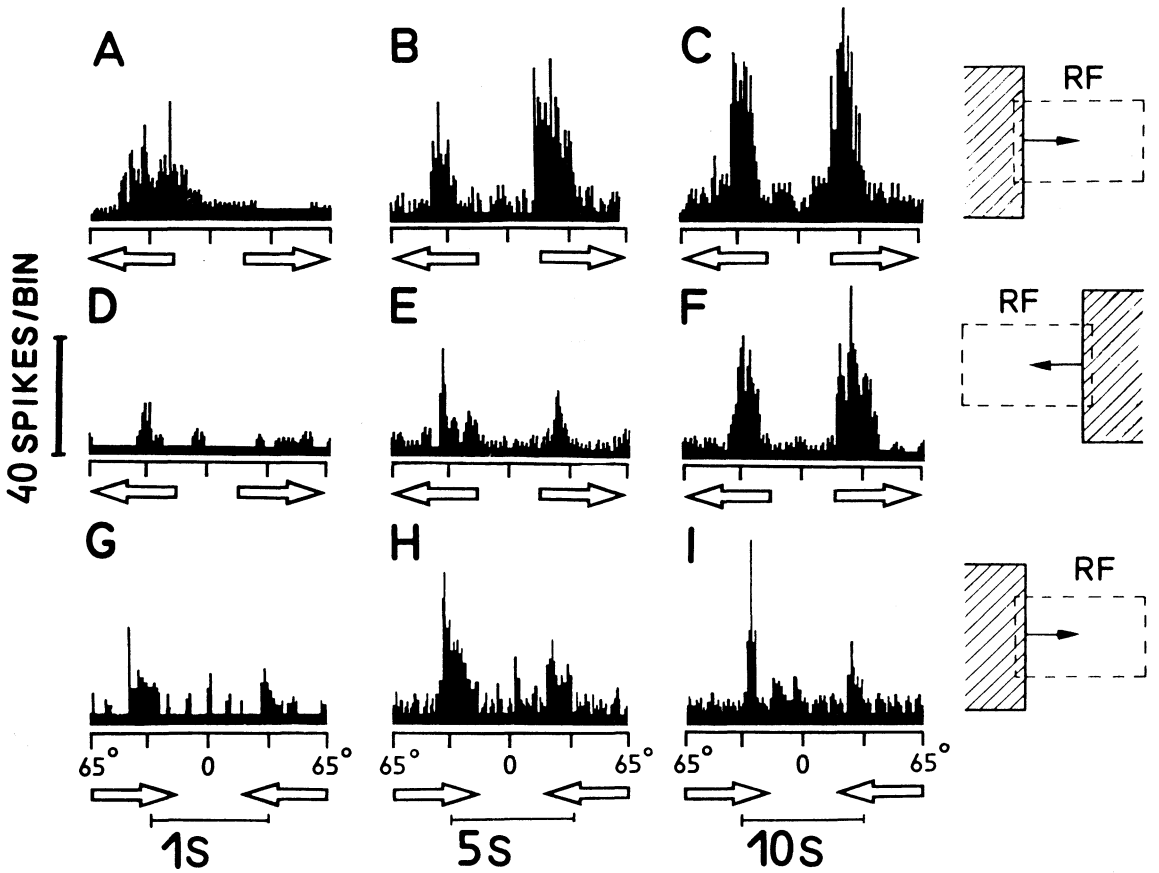

Fig. 4. PSTH of responses of two hippocampal neurones to the different velocities of movement of dark edges along the horizontal axis of their receptive fields. A, B, C, responses of the first neurone to the the motion of dark edge entering into the receptive field from its left border with the different velocities: 65°/s (A), 13°/s (B) and 6.5°/s (C). D, E, F, responses of the same neurone to the movement of the dark edge entering the receptive field from its right border with the velocities 65°/s (D), 13°/s (E) and 6.5°/s (F). G, H, I, responses of another hippocampal neurone to the motion of the dark edge entering into its receptive field from the left border with the velocities 65°/s (G), 13°/s (H) and 6.5°/s (I). The direction of the dark edge motion is shown schematically on the right side of the figure.

DISCUSSION

There is considerable experimental evidence which suggests that the limbic system plays an important role in the processes of learning and memory (O'Keefe and Dostrowski 1971, O'Keefe and Nadel 1978, Oniani 1980, Heit et al. 1988, Squire 1992, Bernard and Wheal 1994). In this context some authors emphasised the significance of the sensory inputs of the limbic system, as the crucial factor in the integration of information and memory process (Cuenod et al. 1965, MacLean and Creswell 1970, Vinogradowa 1975, Gray 1984, Gray and Rawlins 1986, Shen et al. 1994).

The results presented here confirm previous investigations concerning sensitivity of dorsal hippocampal neurones to certain modalities of sensory stimulation (Green and Machne 1955, Vinogradova 1965, McLean et al. 1968, Kopytova and Kulikova 1970, Dubrovinskaya 1971). The present data show that hippocampal neurones show high sensitivity to moving visual stimuli as well as different reactions to the different orientations of applied stimuli. A change in the orientation of stimulus motion (visual angle in relation to the horizontal axis of RF) caused the response pattern of cells to change, which is evidence for high level processing mechanisms of visual information in this region of the brain.

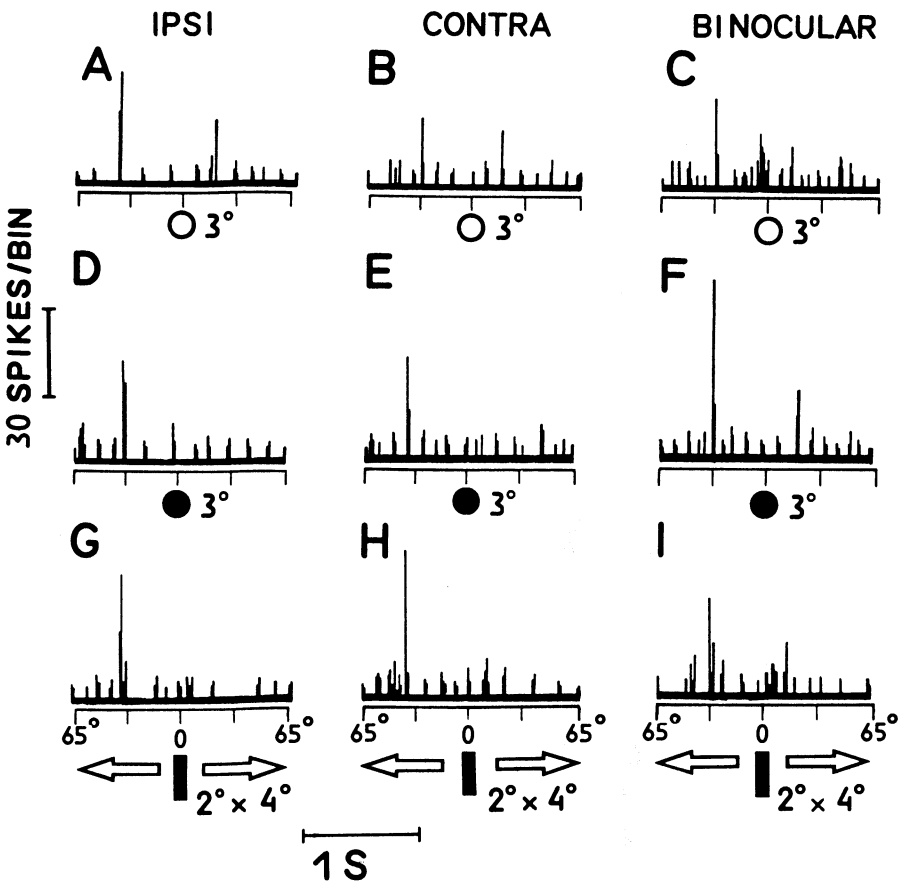

Fig. 5. Ocular dominance effects in the responses of a visually driven hippocampal neurone. A, D, C, responses to the ipsilateral eye stimulation. B, E, H, responses to the stimulation of the contralateral eye. C, F, I, responses to the binocular stimulation. Light and dark spots and bars moving across the horizontal axis of the receptive field were used.

Furthermore, the results of some experiments presented here could be interpreted as revealing the basis, of neuronal mechanisms for processing of shapes and magnitude of visual stimuli. For example, the size of the applied visual stimulus could essentially change the responses of the hippocampal neurones by transforming a directionally sensitive response into a direction non-sensitive one. Moreover, the ocular dominance could also influence the pattern of response of some neurones.

Thus, the data presented here, to some extent prove the existence of highly organized visual sensory input to the hippocampus, which is in accordance with the known morphological data concerning the pathways from visual to the limbic system. A number of morphological investigations provided data according to which there exist pathways from the lateral geniculate body to the limbic cortex (Cuenod et al. 1965, Marty et al. 1969, MacLean and Creswell 1970). Limbic cortex in turn was shown by many researchers to be the main source of afferent fibres to the hippocampus proper (Adey and Meyer 1952, Blackstad 1956, MacLean et al. 1968). Although these pathways are polisynaptic the visual sensory input seems to preserve its highly organized character, and therefore may be involved in central processing of information, i.e. in the integration, selection and memory processes, that most probably take place in the hippocampus.

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