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The effects of stimulus novelty and familiarity on neuronal activity in the amygdala of monkeys performing recognition memory tasks

F.A.W. Wilson*, E.T. Rolls

Department of Experimental Psychology, South Parks Road, Oxford OX1 3UD, UK

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Abstract. The function of the amygdala in behavioural responses to novel stimuli and its possible function in recognition memory were investigated by recording the responses of 659 amygdaloid neurons in monkeys performing recognition memory and visual discrimination tasks. The aim was to determine the contribution of the amygdala in the encoding of familiarity and therefore its role in supporting memory-related neuronal mechanisms in the basal forebrain. The responses of three groups of neurons reflected different forms of memory. One group ($n=10$) responded maximally to novel stimuli and significantly less so to the same stimuli when they were familiar. The calculated memory spans of these neurons were in the range of 2–10 intervening trials, and this short-term retention of information may reflect the operation of a neural mechanism encoding memory for the recency of stimulus presentation. Two other groups responded to the sight of particular categories of familiar stimuli: to foods ($n=6$) or to faces ($n=10$). The responses of some of these stimulus-selective neurons declined with repeated presentations of foods (3/4 tests) and faces (2/6 tests). The activity of these latter two groups of neurons may be involved in behavioural responses to familiar visual stimuli, particularly when such stimuli have affective or motivational significance. We conclude that the neurophysiological data provide evidence of amygdaloid mechanisms for the recognition of recently seen visual stimuli. However, these amygdaloid mechanisms do not appear to be sufficient to support the performance of long-term recognition memory tasks without additional and complementary functions carried out by other ventromedial temporal, prefrontal and diencephalic structures which also project to the basal forebrain.

Key words: Basal forebrain – Neurophysiology – Recognition memory – Single-unit recording – Temporal lobe – Monkey

Present address: Section of Neurobiology, Yale University Medical School, 333 Cedar St., New Haven, CT 06510, USA

Correspondence to: Fraser Wilson

Introduction

Changes in emotionality, and particularly a marked docility, are consistent effects of therapeutic neurosurgery of the amygdala in man (Mark and Ervin 1970). The assessment of the cognitive effects of amygdalectomy in humans is difficult, as epileptic patients undergoing such surgery are often intellectually debilitated owing to their disease or the drug regimens used to control their epilepsy. However, the patient H.M., who underwent bilateral resections of the amygdala, hippocampus and medial temporal cortex, did not show an intellectual decline following surgery, although the lesions resulted in a dense anterograde amnesia (Scoville and Milner 1957) and a remarkable placidity (Corkin 1984). Similarly, severe damage to the amygdala in monkeys does not produce obvious motor or perceptual defects, and amygdalectomised animals, although impaired in the performance of certain associative learning paradigms (Gaffan et al. 1989; Jones and Mishkin 1972; Spiegler and Mishkin 1981; Weiskrantz 1956), are able to learn a variety of cognitive tasks (Murray 1990; Squire and Zola-Morgan 1983). As is the case of human patients, amygdalectomised monkeys are remarkably docile (Aggleton and Passingham 1981; Horel et al. 1975; Kling 1972; Murray and Mishkin 1984; Weiskrantz 1956). Thus, although the amygdala appears to play some role in emotional behaviour (Rolls 1990a), the cognitive functions of the amygdala are not well understood.

However, several findings have suggested that the amygdala plays a role in recognition memory function, in that lesions which damage both the amygdala and the hippocampus (Mishkin 1978; Zola-Morgan and Squire 1985), or both the amygdala and the medial temporal cortex (Murray and Mishkin 1986) produce severe deficits in object recognition tasks in monkeys, although damage largely restricted to either the amygdala or the hippocampus has a milder or even no effect (Mishkin 1978; Murray and Mishkin 1984; Zola-Morgan and Squire 1986). A similar phenomenon is also apparent in human patients, in that lesions of the hippocampus that

spare the amygdala produce a relatively mild memory deficit (Zola-Morgan et al. 1986), while the effect is more severe when the lesions include both hippocampus and amygdala (Duyckaerts et al. 1985) and devastating when the medial temporal cortex is additionally compromised (Scoville and Milner 1957). A recent study of a patient with bilateral lesions restricted to the amygdala has documented an impairment of non-verbal visual memory, including an impairment in the Warrington Recognition Memory test (Tranel and Hyman 1990). Finally, electrical stimulation of the amygdala can elicit the sensation of déjà vu (Gloor et al. 1982; Halgren et al. 1978), suggesting that it contributes to the subjective experience of familiarity.

Further evidence implicating the amygdala in recognition memory comes from the effects of destruction of pathways from the hippocampus and amygdala to the diencephalon. Bachevalier et al. (1985) showed that combined lesions of the fornix and the amygdalofugal pathways produce an impairment in an object recognition task that far exceeds the effects of a lesion restricted to one set of fibres alone. One corollory of this finding is that putative mnemonic information processed by the amygdala is transmitted to diencephalic structures via the amygdalofugal pathways. We were particularly interested in this possibility, for our studies have shown that neurons with marked memory-like properties are located in the basal forebrain, that is, the periventricular region adjacent to the walls of the anterior third ventricle, the substantia innominata and the diagonal band of Broca (Rolls et al. 1982; Wilson and Rolls 1990a,b), structures through which the amygdalofugal fibres course and which they heavily innervate (e.g. Price and Amaral 1981). In these neurophysiological studies, monkeys performed serial visual recognition memory tasks in which they had to distinguish between presentations of objects and pictures on the basis of their familiarity. We observed that the activity of three types of basal forebrain neurons reflected access to recognition memory in that they responded differentially to the novel and familiar stimuli in this task, responses that were maintained over many trials and which indicate access to long-term memory. An injection of the retrograde tracer horseradish peroxidase (HRP) was made into this periventricular region, resulting in the retrograde labeling of cells in the amygdala (Wilson and Rolls 1990a), consistent with the hypothesis that the amygdala plays some role in the recognition-related neuronal activity in the basal forebrain. Nevertheless, the role of the amygdala in recognition memory is not yet fully understood, in that Zola-Morgan et al. (1989) showed that ablations of the amygdala which avoided damage to the overlying entorhinal and perirhinal cortices did not impair performance on a delayed non-match-to-sample task, and did not potentiate the effects of hippocampal damage on that task. It is possible that if the non-matching task had been made more difficult, for example by using intervening stimuli to make it a serial recognition memory task, by using non-trial-unique stimuli (Murray and Mishkin 1984), or by employing a yes-no picture recognition procedure (Freed et al. 1987) similar to that used in the present study, then a deficit would have been observed. However, the study of Zola-Morgan et al. (1989) does suggest that it is damage to the overlying cortex rather than to the amygdala itself which is implicated in recognition memory.

The aim of the present experiments was to examine the responses of neurons in the amygdala during the performance of recognition memory tasks. We reasoned that if the amygdala plays a role in the encoding of novelty or of familiarity, the recognition memory task we used in the basal forebrain recordings should reveal related neuronal activity in the amygdala. Some of the data described here have been reported in abstract form (Wilson and Rolls 1987).

Materials and methods

Subjects, stimulus presentation and behavioural tasks

Two male rhesus monkeys (weight 4 kg) were trained to perform visual discrimination and recognition memory tasks for the delivery of fruit juice. During the experiment the monkeys sat in a chair, the top, front and sides of which were enclosed by metal shielding. Their view of the laboratory was limited to a circular aperture in the shielding. Visual stimuli were presented with a fast (~10 ms) rise time, 6.4-cm-diameter electromagnetic shutter mounted over the aperture. The shutter was removable, allowing the presentation of objects and the delivery of foods to the monkey through the aperture. The stimuli were presented individually, one per trial, with an intertrial interval of 6 s. Each trial began with a 0.5-s tone cue followed by the opening of the shutter for 1.5 s. During the stimulus presentation, the monkey was able to respond by licking a tube through which either fruit juice or saline was delivered, depending upon the learned meaning of the stimulus.

Training began by seating the monkeys in a primate chair in the laboratory and familiarising them with the reinforcement value of two distinctive syringes differing in shape and colour. Initially the syringes were held in the hand of the experimenter, one syringe (the S+) being used to deliver juice to the mouth, the other being used to deliver saline (the S–). The monkeys rapidly learned to discriminate the valence of these syringes, and would reach for or turn away from the approaching S+ or S– held by the experimenter.

Formal training in the *visual discrimination task* began by using the shutter to present the S+ and S– syringes to the monkeys. They learned to lick the tube at the sight of the S+, for which juice was delivered, and to refrain from licking at the presentation of the S–, thus avoiding the delivery of saline.

Performance of the *serial recognition memory task* required the monkeys to distinguish between novel and familiar presentations of objects. Each stimulus was shown only twice per day, and the monkeys learned to use their memory for the familiarity of the stimuli to guide their behavioural responses. Lick responses to novel stimuli resulted in the delivery of saline, while responses to the same (but now familiar) stimuli, when they had been seen recently, elicited juice. Approximately 2000 objects were used as stimuli, varying in size, colour and shape. The entire stimulus set was shown once every 2–4 weeks. Stimuli which had not been seen for this period of 2–4 weeks were treated as novel by the monkeys in that they did not respond to their first presentation by licking in the recognition memory task. Their performance was on average better than 90% correct.

The presentation of a familiar stimulus in the serial recognition memory task could occur immediately (6 s) after the first, novel presentation, or later in the series after a number of other stimuli had been presented. This made the task difficult for the monkeys, who had to rely on their memory for whether they had seen a stimulus recently, and ensured that the monkeys could not predict the occurrence of a familiar stimulus. The serial recognition memory task was run at three levels of difficulty, with the numbers of

intervening trials between the two sucessive presentations of the stimuli ranging from 0 to 2, from 0 to 8, and from 0 to 16. An example of part of one sequence (the 0–8 version) is: N1 N2 F2 N3 N4 F1 N5 F4. The novel stimulus (N1) shown on trial 1 was shown again after four intervening trials as familiar (F1) on trial 6, while the novel stimulus (N2) shown on trial 2 was repeated with no intervening trials on trial 3.

Clinical tests

After the responses of neurons had been determined in the memory tasks, it was often possible to assess the effects of presenting foods, the S+ and the S– syringes, and novel and familiar objects through the aperture in the primate chair, a procedure which we term "clinical testing" and which resembles a routine neurological examination. The term "clinical tests" is used to describe the informal testing that we wish to distinguish from the testing done in the formal memory tasks.

In clinical tests, stimulus presentations were made using a standard protocol in which counts of mean firing rate for a 2-s period were made by computer during the steps in the protocol. The protocol consisted of: (1) the presentation of the experimenter's arm viewed through the aperture; (2, 3) reaching movements to and from the stimulus to be presented, with the stimulus still out of view; (4–6) the sight of the stimulus, its approach, movement of the stimulus close to the mouth and touching the mouth to elicit mouth movements and to test for somatosensory input; and finally (7) delivery of the stimulus into the mouth to produce taste. The stimuli were presented without a preceding tone cue and the delivery of foods to the monkey was not contingent upon a lick response.

Experimental procedures and testing protocols

The monkeys became very proficient at the recognition memory and visual discrimination tasks, such that novel and familiar stimuli, the S+ and S–, and other stimuli such as foods and faces were presented in pseudorandom order during the experiments, and the monkeys performed the two tasks concurrently with a high degree of accuracy (>90%). This procedure enabled a great many stimuli varying in their valence and familiarity to be presented to the monkeys, testing the monkeys' memory for familiarity, and making it unlikely that the monkeys could predict the appearance of a particular type of stimulus.

After the monkeys were fully trained, they were prepared for the neurophysiological experiments, in which recordings were made from single neurons during the performance of the memory tasks. Details of the microelectrodes, amplification, on-line computing, electrooculogram, methods for determining the location of the neurons, etc. were conventional and have been described in detail elsewhere (Rolls et al. 1982; Wilson and Rolls 1990b, c).

Recordings of neuronal activity were made in the globus pallidus, basal forebrain, amygdala and medial temporal cortex while the monkeys performed the memory tasks. Recordings from these four structures often took place during a single pass of the microelectrode through the brain, allowing us to compare their different contributions to the tasks. In this series of experiments our objective was to determine if neurons in the amygdala responded on the basis of the familiarity of the stimuli, but we made no attempt to select amongst the neurons we recorded during the experiments. Neurons were tested during the performance of the memory tasks and clinical tests for 17 trials to assess responsiveness to the stimuli, a procedure that lasted for 10 min. A neuronal response to any of the stimuli presented lead to extensive testing of up to 4 h in order to determine the basis of the response. Action potentials were continuously monitored on a storage oscilloscope to ensure the stability of the recording of a single neuron.

Data analysis

The computer sampled the occurrence of neuronal spikes every 10 ms, starting 200 ms before the onset of the visual stimulus and 700 ms after its presentation. The number of spikes emitted in a 500-ms period starting 100 ms after stimulus presentation were counted and used as the measure of the neuronal response. These data were subsequently treated to statistical analysis, in which the trial-by-trial responses to the novel and familiar stimuli, the S+ and S– were entered into a computer, which carried out a one-way analysis of variance (ANOVA). In order to determine which stimulus group was responsible for a significant result in the ANOVA, the Tukey test (Bruning and Kintz 1977) was applied to test the significance of any difference between the means of the various groups. The ANOVAs of all responsive neurons in this paper resulted in F values significant at a level of $P>0.01$ or more.

The latencies at which neurons responded differentially to novel as opposed to familiar stimuli were determined with the use of cumulative sum techniques (Woodward and Goldsmith 1963) implemented on a computer. Peristimulus time histograms were computed for each type of trial and subtracted from each other; the cumulative sum of this difference array was then calculated to allow estimation of the differential response latency.

Results

Overview

Of the 659 neurons recorded in 92 microelectrode penetrations of the amygdala, the activity of relatively few ($n=43$) was found to be specifically related to the performance of the recognition memory task, the visual discrimination task or the properties of the stimuli presented in these tasks. Although 277 neurons (42%) were responsive during the tasks, the basis of the majority of these non-selective responses was not evident with the behavioural tasks and the extensive range of visual stimuli we employed. Table 1 lists the categories of neurons recorded.

Table 1. Summary of the responses of 659 amygdaloid neurons during behavioural tasks

Category of neurons	Number of neurons
Novelty-responsive and stimulus-specific neurons	
Differential responses based on stimulus novelty	10
Stimulus-specific responses to faces	10
Stimulus-specific responses to foods	6
Differential responses to the S+ and S–	17
Non-selective responses	
Responses during the presentation of visual stimuli	122
Responses during the presentation of the tone	72
Responses during the clinical tests	19
Responses during licking	12
Responses to auditory stimuli	7
Responses to tactile stimuli	2
Unresponsive neurons	382
Total number of recorded neurons	659

S+, syringe containing fruit juice; S–, syringe containing saline

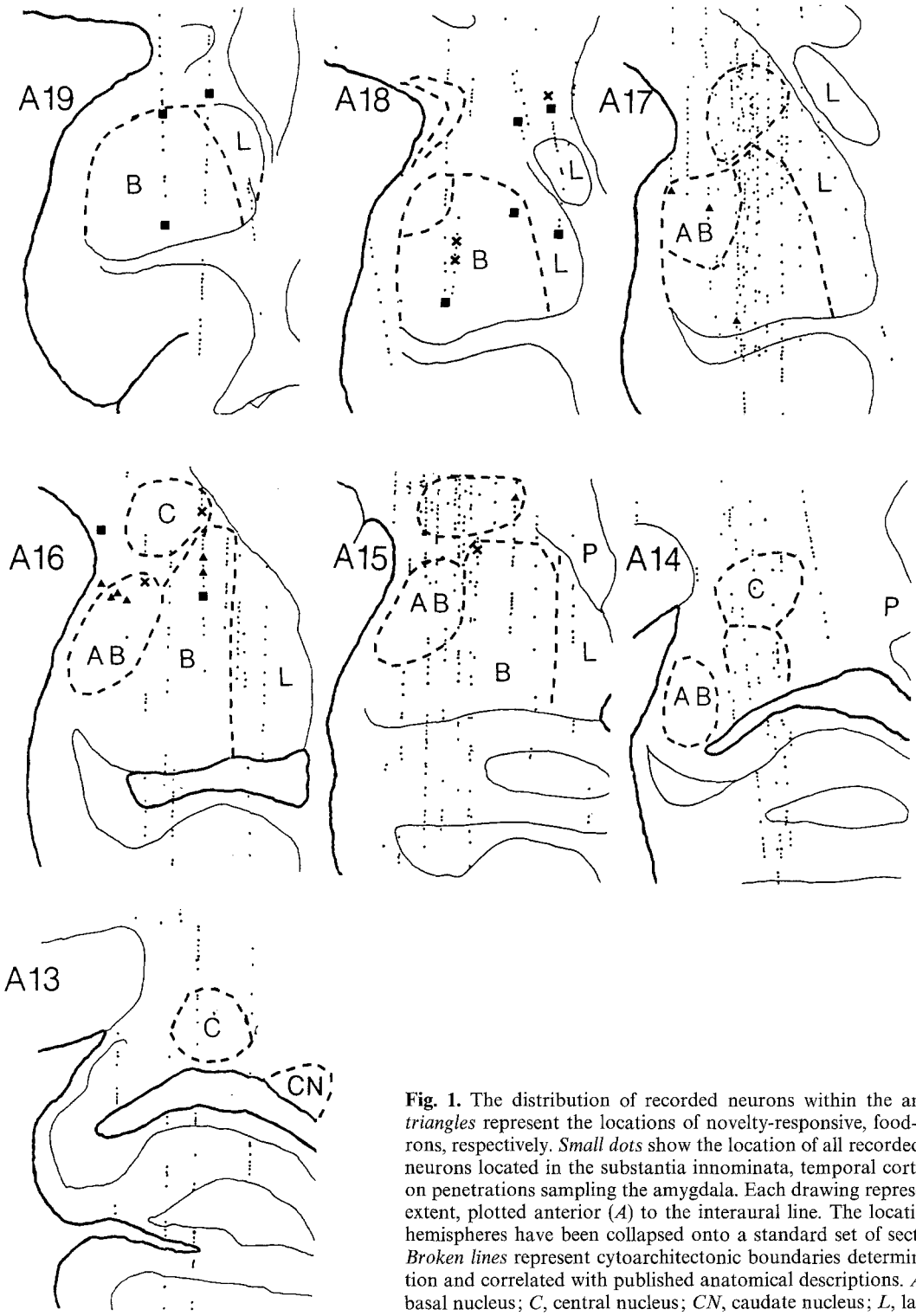

Fig. 1. The distribution of recorded neurons within the amygdala. *Squares, crosses* and *triangles* represent the locations of novelty-responsive, food-selective or face-selective neurons, respectively. *Small dots* show the location of all recorded neurons, including additional neurons located in the substantia innominata, temporal cortex and hippocampus recorded on penetrations sampling the amygdala. Each drawing represents a section of brain 1 mm in extent, plotted anterior (*A*) to the interaural line. The locations of the neurons from three hemispheres have been collapsed onto a standard set of sections from the left hemisphere. *Broken lines* represent cytoarchitectonic boundaries determined after histological examination and correlated with published anatomical descriptions. *AB*, accessory basal nucleus; *B*, basal nucleus; *C*, central nucleus; *CN*, caudate nucleus; *L*, lateral nucleus; *P*, putamen

The main aim of the experiments was to investigate whether neuronal activity that reflects the novelty or the familiarity of visual stimuli is present in the primate amygdala. We found that two different types of neurons reflected this dimension of the stimuli. The activity of one group encoded the relative novelty of visual stimuli. A second type of neuron responded specifically to the sight of particular categories of familiar stimuli, i.e. foods or faces.

Location of the recorded neurons

The recordings sampled the central core of the amygdala, and particularly the dorsal region. The most anterior, ventral, medial and lateral margins were examined less completely. The locations of all recorded neurons are shown in Fig. 1, along with the locations of those neurons that responded to novel stimuli or to specific visual stimuli described in this paper. Neurons that were maximally

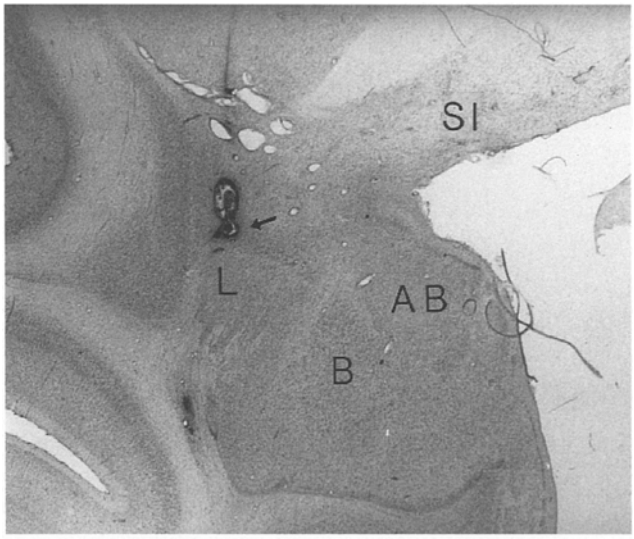

Fig. 2. A marker lesion made at the site of neuron 351. This neuron responded maximally to the sight of novel stimuli in the recognition memory task, with a decrement in response to familiar stimuli. The lesion (see *arrow*) is located in the dorsal amygdala at the border of the lateral nucleus and anterior amygdaloid area medial to the claustrum. *AB*, accessory basal nucleus; *B*, basal nucleus; *L*, lateral nucleus; *SI*, substantia innominata

responsive to novel stimuli were located primarily in the anterior region of the basal nucleus (2 at A19; 2 at A18; 1 at A16); in the lateral nucleus (1 at A19; 3 at A18); and one was in the medial nucleus (A16), which was distinctive in having a particularly long response latency. Food-selective neurons were found in the dorsal region of the lateral nucleus (1 at A18); in the basal nucleus (2 at A18; 1 at A15) and accessory basal nucleus (1 at A16); and in the lateral central nucleus (1 at A16). Face-selective neurons were located dorsomedially: six were in the accessory basal nucleus (A17 and A16); three were in the basal nucleus (A17 and A16); and one was in the lateral central nucleus (A15). Due to the use of a standardised series of sections to represent the locations of the recording sites, certain neurons are displaced, i.e. are plotted at the borders of the structures in which they were actually located. Figure 2 shows a lesion made at the site of a neuron that responded maximally to novel stimuli in the recognition memory task.

Short-term encoding of novelty and of recency

Ten neurons were recorded that responded maximally to the first presentation of visual stimuli, reflecting the novelty of the stimuli. These neurons responded to any novel stimulus shown in the recognition memory task, irrespective of the size, shape and colour of the stimuli. The neuronal response to novel stimuli persisted for many hundreds of milliseconds, but when the same stimuli were shown a second time as familiar, the neuronal response was different, being more transient and of smaller amplitude. For example, the neuron shown in Fig. 3A responded to both novel and familiar presentations of the stimuli with an onset latency of 110 ms, and a difference in the responses to novel and familiar stimuli began at 250 ms, based on cumulative sum histograms (see Materials and methods). The response to familiar stimuli ceased at approximately 300 ms, while the neuron continued to respond to novel stimuli. This differential neuronal response latency precedes the mean lick response latency by 120 ms for these data. The responses of seven of these ten neurons to familiar stimuli were increases in firing above the spontaneous firing rate, indicating that a "decision" about the novelty or familiarity of the stimulus is reflected in the neuronal activity some time after the onset of the response (see the analysis of the time course of the neuronal responses outlined below). In all cases these differential responses to novel and familiar presentations were significantly different (ANOVA and Tukey tests); the magnitudes of the responses to novel and familiar stimuli of these ten neurons are shown in Table 2.

The time course of these responses was examined with cumulative sum histograms (see Materials and methods). The mean onset latency of the responses to the stimuli in the recognition memory task was 138 ms (range 130–180 ms). The differential response latency was determined as the point at which the neuron responded differentially to novel and to familiar stimuli, i.e. when the neuronal response on familiar trials terminated. The mean differential response latency was 212 ms (range 150–380 ms); the mean spontaneous activity of these ten neurons was 15.3 spikes/s (range 6.8–32.9 spikes/s).

We found that the different reinforcement values of novel and familiar stimuli were not responsible for the differential responses to the same stimuli. This was established by recording the activity of these neurons during the performance of the visual discrimination task, in which the discriminative stimuli (the S+ and the S–) differed in their reinforcement value but which were equally and highly familiar to the monkeys. Figure 3B illustrates the responses of neuron 4a to the S+ and S– in the visual discrimination task. The neuron responded equally to the S+ and S–, although the monkey responded quite differently to the two stimuli, with lick responses to the S+ and no responses to the S–. It is notable that the neuron responded to both the S+ and S– with a transient, 200-ms burst of activity. This burst of activity is similar to that elicited by the presentation of the familiar stimuli in the recognition memory task. In all cases, the response of these neurons to novel stimuli were significantly greater than to familiar stimuli, and in most cases this was also true for the differential response between novel stimuli compared with the S+ and S– (see Table 2). In some cases, the responses to the S+ and S– were large when they had not been recently seen, but these responses declined when the stimuli were shown repeatedly on two consecutive trials, irrespective of their different reinforcement values. Thus the familiarity of the stimuli or the recency of their presentation, but not their differential reinforcement value, is the basis of the neuronal responses to novel stimuli. It will also be noted that the neuronal activity is not related to the lick responses. The monkeys did not make lick responses on novel and S– trials, yet these differential neurons responded strongly to novel stimuli, and less so to the S– which was highly familiar.

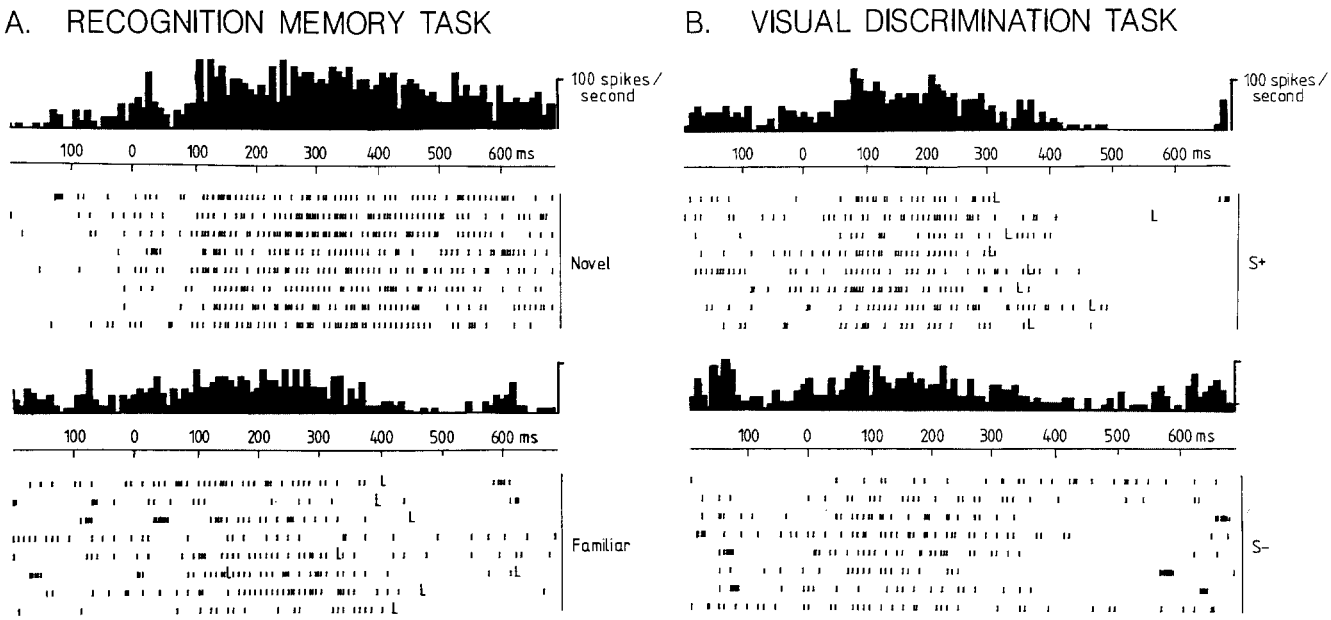

Fig. 3A, B. Responses of neuron 4a responding maximally to novel stimuli in the recognition memory and visual discrimination tasks. *Each tick mark* represents the occurrence of an action potential; *each row* represents the neuronal responses on a single trial to the presentation of novel or familiar stimuli and the syringes containing fruit juice or saline (S+, S–, respectively) presented at time zero. **A** In the recognition memory task, presentations of eight different novel stimuli elicit prolonged bursts of firing, with smaller, transient increases in firing rate to the same eight stimuli when shown as familiar. **B** In the visual discrimination task the neuron responds transiently to presentations of the highly familiar S+ and the S–, similar to the responses to familiar stimuli shown in the recognition memory task. The presentation of the stimuli occurred in pseudorandom order, but trials are grouped for clarity. In the recognition task, eight stimuli were shown, first as novel and then as familiar; the order of presentation is the same for both novel and familiar trials. *L* indicates the occurrence of the lick response. The *scale at the right* of the histogram represents a firing rate of 100 spikes/s; bin width 10 ms

Table 2. Responses of neurons (mean-firing rate) with activity related to novelty/recency to different types of stimuli in the recognition memory and visual discrimination tasks

Neuron	S.A. (spikes/s)	Novel (spikes/s)	Familiar (spikes/s)	S+ (spikes/s)	S− (spikes/s)
2	21.6	29.8	22.2	22	30.6
4a	12.5	80.6	47	72.4	32
4b	25	56.6	36.4	nt	nt
84	11.8	49.4	30.6	36.6	nt
94	8	28.6	18.4	17	16.8
271a	8.2	46.8	37.2	27.4	31.6
271b	15	40.2	31.2	23.6	16.4
319	8	20.9	11.7	16.3	15.4
338	15.4	55.8	40.8	28.6	30.8
351a	14.4	28	17.6	17.4	nt

S.A., spontaneous activity; nt, not tested, or insufficient data; S+, syringe containing fruit juice; S−, syringe containing saline

Measurement of the "memory spans" of the novelty-responsive neurons

The large differential response to novel and familiar stimuli occurred with an intertrial interval of 6 s between the two presentations of any given stimulus, indicating a memory for the stimulus that endured for the 6-s interval between trials. The capacity of monkeys with amygdalo-hippocampal lesions to recognise a stimulus is particularly impoverished when distractor items occur between the first and second presentations of a stimulus (Mishkin 1978; Murray and Mishkin 1984). Thus we examined the differential neuronal activity to see if it was affected by intervening stimuli, all of which had to be remembered. The firing rates of five neurons were determined in response to presentations of familiar stimuli that had not been seen for a number of trials, the maximum being 16. We found that, for each neuron, the magnitude of the differential response was attenuated by the distracting, intervening stimuli.

Figure 4 shows the data from one experiment in which the "memory span" (see below) of a novelty-responsive amygdaloid neuron (319) was estimated. A total of 68 different stimuli were shown twice, once as novel and

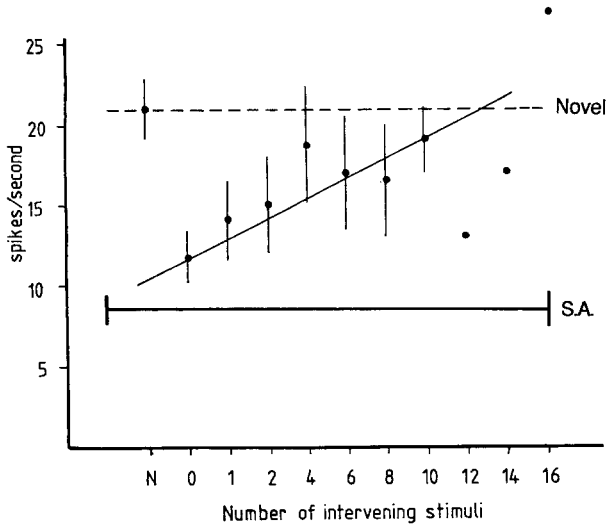

Fig. 4. The decline of the differential response to novel and familiar stimuli due to intervening trials (neuron 319). Each data point represents the mean (and standard error of the mean) for stimuli shown as novel or as familiar after various numbers of intervening trials. The differential response is maximal when no trials intervene (intertrial interval 6 s), but is progressively attenuated as the number of intervening trials increase. The correlation between firing rate and the number of intervening trials is significant ($r=0.36$; $P<0.05$), obtained by presenting 68 novel stimuli, first as novel and subsequently as familiar. *S.A.*, spontaneous activity

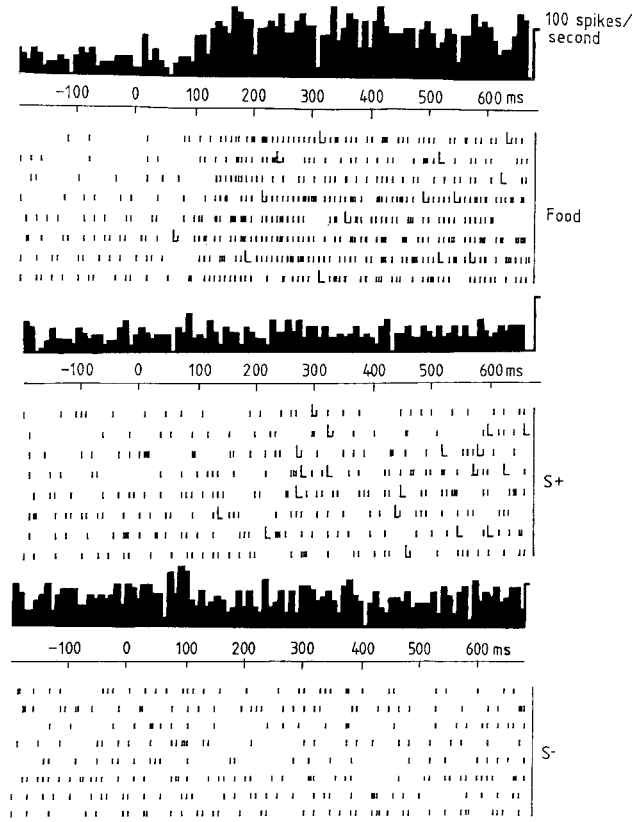

Fig. 5. The responses of a food-selective neuron (264) to foods, and the syringes with fruit juice and saline (S+ and S–). The stimuli were presented in pseudorandom order but are grouped for clarity. Each *row of ticks* represents a single trial; each *tick* represents the occurrence of a single action potential. The neuron responds with an increase in firing rate to the sight of small pieces of food (peanut, orange, banana), but not on S+ trials nor on S– trials. The monkey licks on trials in which foods and the S+ were presented, but as the neuron responded only at the sight of foods, the recognition of the food is the basis of the neuronal activity, and not the reinforcement value of the stimuli nor the lick responses

again as familiar. Each data point represents the mean response to familiar stimuli shown after a given number of intervening trials. The large neuronal response to novel stimuli was not elicited when the stimuli were shown as familiar (no intervening trials) without the occurrence of distractor items; but gradually, as other trials intervened between the novel and the familiar presentations of the stimuli, the response to familiar stimului became larger, and more like that to the novel stimuli (see Fig. 4). A linear regression calculated on these data was used to estimate the point at which the neuron responded to a familiar stimulus as if it were novel. This number of trials was defined as the "memory span" of the neuron, which was ten trials for neuron 319 (Fig. 4). Of the five differential neurons for which this analysis was done, the average memory span was estimated to be five intervening trials (range, two to ten intervening trials), with a duration of approximately 80 s for the neuron with the most robust "memory span".

The magnitude of the differential responses between novel and familiar stimuli might be expected to remain constant or even to increase for stimuli that become increasingly familiar to the monkey. To test this hypothesis, certain stimuli were repeatedly shown for up to nine presentations without intervening trials with the usual intertrial interval of 6 s. We found the change in response to familiar stimuli was largest on the trial in which the stimulus was first shown as familiar, and that repeated presentations of the same stimulus produced relatively little further change in response (see, for example, Fig. 6). Thus a single, 1.5-s presentation of a stimulus was sufficient to induce the maximal change in the neuronal response to familiarity.

Stimulus-selective neuronal responses to foods

During the course of the experiments, presentations of food were interdigitated amongst those of the stimuli in the recognition memory and visual discrimination tasks. In this way, six neurons were found that responded maximally to the sight of small pieces of foods that were frequently fed to the monkeys in clinical tests (see below). Such neurons were relatively unresponsive to the S+ and familiar stimuli in the visual discrimination and recognition memory tasks, stimuli that signalled the availability of juice to the monkey, as did the presentations of foods. Figure 5 shows an example of a neuron which responded to presentations of different foods to which the monkey licked, obtaining juice. However, the neuron was unresponsive to presentations of the S+ (which elicited licking) and to the S– (which did not elicit licking). It is clear that the lick responses made at the sight of foods and the S+ were not the basis for the neuronal response to foods. In that these neurons did not respond to the S+ (see Fig. 5), and usually did not respond strongly to all foods (e.g.

Table 3. The mean responses of food-selective neurons to different tests

	Neuron					
	95	264	274a	274b	307	351b
A. *Responses to stimuli presented in the discrimination and recognition tasks (spikes/s)*						
S.A.	36.8	34.5	16.4	6.9	24.3	1.8
Foods	23.9	70.8	38.3	34.3	15	26.3
S+	44.5	39.6	15.8	11.6	30.4	7.8
S−	32	30.2	13.4	3.4	29.4	nt
Novel	33	42	21.2	17.2	17.8	29
Familiar	48.5	43.8	18.6	10.6	29	14
B. *Responses to different foods presented during the performance of the behavioural tasks (spikes/s)*						
Apple	nt	66	38	nt	nt	nt
Banana	17	83	37.6	22	9	nt
Bread	nt	nt	nt	47.2	nt	nt
Chocolate	nt	nt	nt	nt	nt	34
Nut	25	55.3	39	nt	25.2	29.4
Orange	nt	60.6	41	37.2	19.2	12
Raisin	24.2	nt	nt	nt	nt	nt
C. *Responses to foods and other stimuli presented in the clinical tests (spikes/s)*						
Foods	24	49	24.3	35	12.9	nt
S+	31.6	37	23	11	24.1	nt
S−	30.2	35	21	4.7	nt	nt
Objects	31	nt	nt	10.1	23	nt

S.A., spontaneous activity of the neuron; nt, not tested, or insufficient data

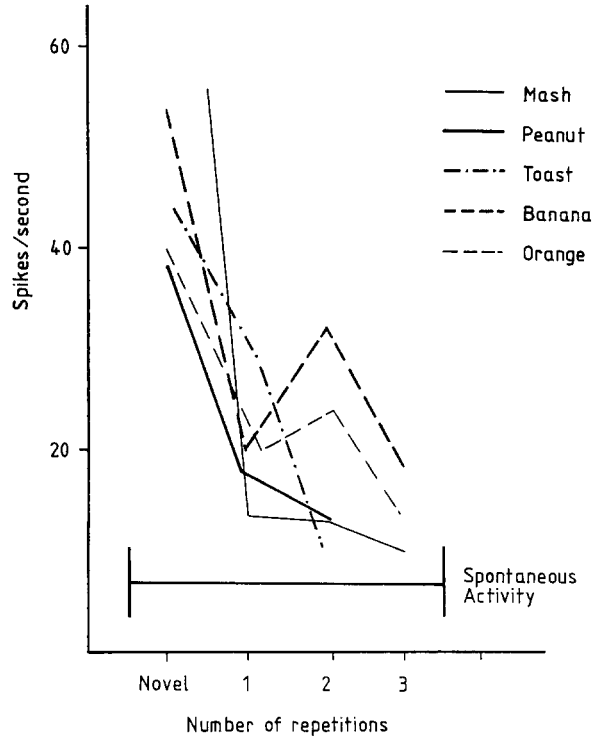

Fig. 6. The decremental responses to repeatedly presented foods (neuron 272). Each of five different foods was presented three or four times on sucessive trials, with presentations between different foods interdigitated with other stimuli during the performance of the recognition memory task. The main effect of repetition is a large decrement in response to first, "familiar" presentation of each stimulus

Fig. 7, Table 3B), they did not respond on the basis of the reinforcement value of the stimulus being shown.

In most cases food-selective neurons responded with transient, phasic increases in firing rate to foods. Two neurons (95 and 307) responded to foods with decreases in firing rate (e.g. Fig. 7). The mean spontaneous firing rate of the neurons was 20.2 spikes/s (range 1.8–36.8 spikes/s). The mean onset latency to the sight of foods was 134 ms (range 120–150 ms); the mean differential response latency at which the neuronal responses to food differed from other visual stimuli was 148 ms (range 140–190 ms).

In all cases, the responses to foods were significantly different (ANOVA and Tukey tests) from the responses to the S+, and to familiar stimuli, which indicates that the learned reinforcement value of food stimuli (i.e. they are familiar and signal the availability of juice) does not account for the neuronal responses. The neuronal responses to foods and the S– also differed significantly, but it was notable that the responses to the aversive S– were markedly different from to the S+ and familiar stimuli, as in most cases the food-selective neurons were completely unresponsive to the S–, while the S+ and familiar stimuli generally elicited a minor response. In this sense, therefore, the reinforcement value of the stimuli may play a role in the neuronal responses to the different stimuli. Furthermore, novel stimuli elicited neuronal responses that approached in magnitude the responses to foods in three neurons. The neuronal responses to foods and to other stimuli are compared in Table 3A.

The repeated presentation of a food resulted in a decrement in firing rate in three of four food-selective neurons that were tested (e.g. Fig. 6). A *t*-test on the neuronal responses to the first and second presentations showed that the decrement in response was significant in these three neurons. Although the decrement in response to the second presentation of the stimulus was large, further repetitions resulted in only minor decrements in response, and always a decline rather than an increase. For one neuron (351b), the decrement in the response to repeated presentations of foods was not equal for all stimuli; the neuronal response did not decline with repeated presentations of one of the foods (chocolate). These decremental responses did not occur to non-food stimuli, because such stimuli, did not elicit a response to the first presentation.

The magnitude of the neuronal responses differed among the different foods presented during the performance of the memory tasks (Table 3B and Fig. 7). Although certain neurons were maximally responsive to a particular food, other neurons were less responsive to this food and responded maximally to another food. While the monkeys clearly preferred certain foods, as ascertained by lip-smacking responses at the sight of certain foods, the data from this limited number of neurons suggests that overall food preference was not encoded by

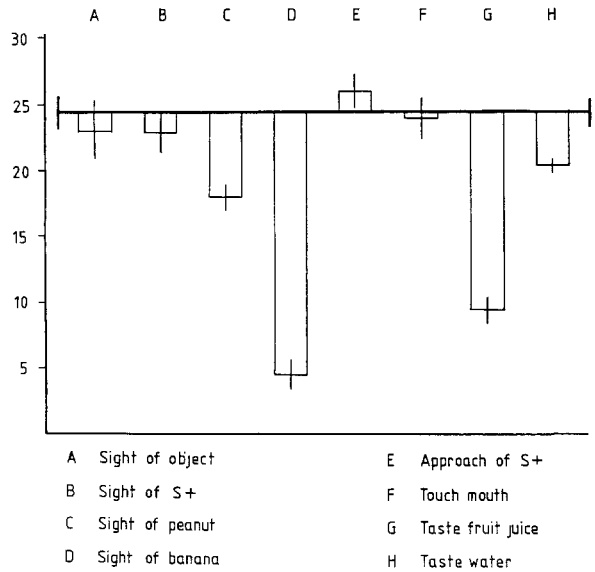

Fig. 7. Responses to the sight of foods in the clinical tests (neuron 307). Each *bar* represents the mean response (and standard error of the mean) to different stimulus events. The neuron responded maximally with a decrease in firing rate to the sight of banana (*D*), with lesser responses to the taste of juice (*G*) and water (*H*). The neuronal activity does not encode the reinforcement value of the stimuli per se, as the sight of the S+ (*B*) does not elicit a marked neuronal response, even though the sight of the S+ signals the availability of juice. *A*, sight of objects; *C*, sight of peanut; *E*, approach of S+; *E*, touch mouch

these neuronal responses, and that they were selectively responsive to the sight of different foods.

Table 3C details the responses of neurons to the presentation of foods, the S+, S– and objects in the clinical tests when the shutter had been removed and the monkey was being fed through the aperture in the chair. In this situation, the responses to foods were still elicited, the mean percentage change being 45% relative to the spontaneous firing rate of each neuron. For comparison, the mean responses to presentations of the S+ and S– were 17.8% and 16%, respectively. The data in Table 3C show that the responses to sight of the S+ and S– are similar in the clinical tests, and different from the neuronal responses to foods. We also found that the responses to the approach of food, the manipulation of the mouth with the foods, and the taste of foods were not particularly effective in eliciting responses from five of the six selective neurons. However, one neuron (307) was responsive both to the sight of food and the taste of juice (Fig. 7). This neuron responded to the sight of foods, and particularly to the sight of banana, with a sustained decrease in firing rate for periods of up to 10 s in duration (the maximum period tested) while the food was in the monkey's field of view. A lesser decrease in firing rate also occurred during the drinking of fruit juice from a syringe.

Stimulus-selective neuronal responses to faces

Face stimuli were presented to the monkeys during the routine testing of amygdaloid neurons. The monkeys were able to lick to obtain juice in response to presentations of faces, which were usually familiar to them. Novel faces often elicited emotional behaviours such as lip smacking and grimacing.

Ten neurons were found that responded exclusively or predominantly to the presentation of faces. Figure 8 shows the responses of a neuron that were selectively elicited by one specific face (A.S.), but not to other faces, novel and familiar stimuli, and the S+ and S–. The neuronal activity was not related to the lick responses, as the neuronal firing occurred only at the sight of A.S. (Fig. 8A), although the monkey responded to presentations of most faces (Fig. 8B) with a lick. Furthermore, the neuronal responses to novel stimuli and the S– (Fig. 8C,D) were identical to those elicited to the ineffective faces (Fig. 8B), but whereas the monkey licked in response to faces, such responses were not made to the novel stimuli and the S–.

In all ten cases, faces elicited increases in firing rate in these selective neurons. In most cases the neuronal responses consisted of short periods of firing (e.g. 1.5 s or less) which were closely time-locked to the presentation of the stimuli. In one case, the response was sustained while the face was in the monkey's view for 5 s, even when the monkey's eyes were averted and did not directly fixate the face. The mean onset latency for the neuronal responses to faces was 159 ms (range 130–200 ms); the mean differential latency at which the neurons responded differently to faces compared with other stimuli was 190 ms (range 140–210 ms). The mean difference between onset and differential latencies was 33 ms, indicating that the response to non-face stimuli was usually minor.

The majority of these selective neurons were tested in the visual discrimination (9/10) and recognition memory (9/10) tasks; in all cases the responses to faces were significantly greater (ANOVA and Tukey test) than to novel and familiar objects, and to the S+ and S–. Table 4 gives the mean responses of these neurons to the different stimuli and their spontaneous firing rates, which were generally low (mean 7 spikes/s; range 1–13 spikes/s).

Of the ten face-selective neurons, five responded equivalently to all faces. For the other five neurons there were differences in the magnitude of the responses to the various face stimuli. In one case, neuron 303 responded selectively to 1 (A.S.) of a total of 12 other faces shown (Fig. 8). The maximal response (48 spikes/s) occurred when A.S. was located 3 m from the monkey, enabling the monkey to see the upper torso and face of A.S. through the shutter. As the neuron was least responsive (37 spikes/s) to A.S. at a distance of 0.3 m from the monkey, it is unlikely that the neuronal response reflected arousal generated by the nearness of the person to the monkey. For comparison, the responses of neuron 303 to other faces presented 0.3 and 3 m from the monkey were 13 and 15 spikes/s, respectively, baseline activity being 9 spikes/s in these tests. The specificity of this neuron was discovered when it was observed that the monkey vocalised (a bark) and gave an open-mouth threat in response to the sight of A.S. concomitant with a discharge from the neuron. A.S. had worked with the monkey for 5 days prior to the recording of this neuron. The onset and

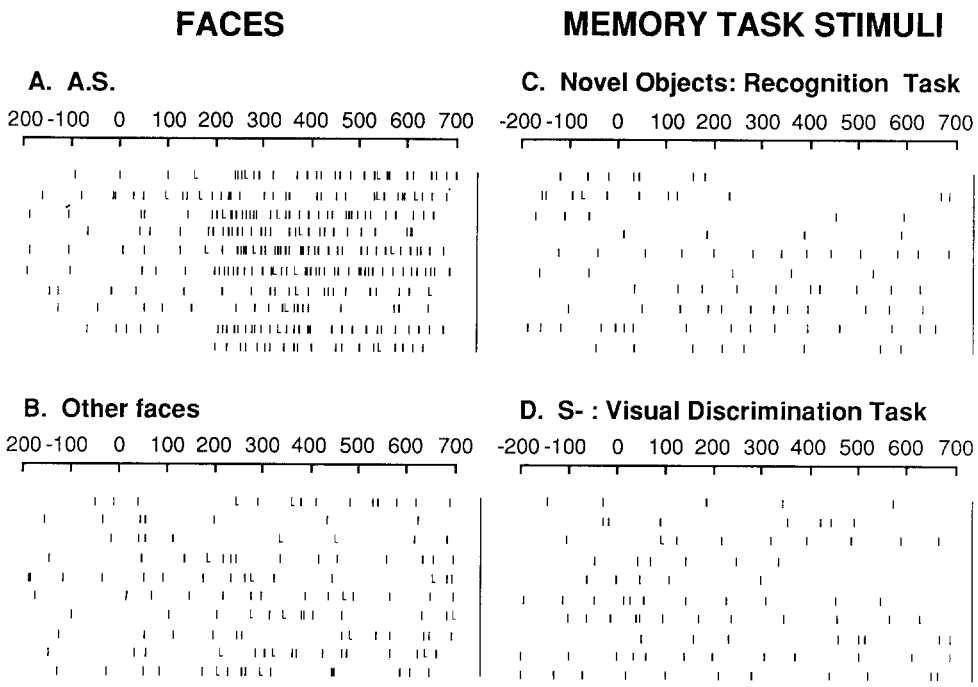

Fig. 8A–D. The responses of a highly specific face-selective neuron (303). The stimuli were presented in pseudorandom order but are grouped for clarity. Each *row of ticks* represents the neuronal responses on a single trial; each *tick* represents the occurrence of a single action potential. **A** Responses to ten presentations of the effective face (A.S.); **B** Responses to ten ineffective face stimuli; **C** Responses to ten ineffective novel stimuli; **D** Responses to the ineffective S–. *L*, the occurrence of the lick response

Table 4. Responses of face-selective neurons (mean firing rate) to different stimuli in the recognition memory and visual discrimination tasks

Neuron	S.A. (spikes/s)	Faces (spikes/s)	S+ (spikes/s)	S− (spikes/s)	Novel (spikes/s)	Familiar (spikes/s)
97	12.9	84.9	50.4	nt	38	37
261	6.2	23.1	5.8	4.8	7.4	7
280	2	28.5	15	8	nt	nt
303	3	47.3	8	6.2	7.1	17.2
304a	17	44.1	20.6	17.2	18.2	14.4
304b	5.3	38.3	17.2	11.2	14.4	14.3
305	1	33.1	9.6	10.8	13.1	14.3
308a	3	22.4	10.2	10	14.5	11.4
308b	12.3	34.6	8.3	12.4	14.5	10
321	7	14.9	7.2	4.9	4.7	8.7

S.A., spontaneous activity; nt, not tested, or insufficient data

discrimination latencies for this neuron were identical (200 ms), consistent with the highly selective responsiveness of this neuron.

During testing, it was found that two of six face-selective neurons responded to repeated presentations of a face with a significant decrement in the response. As with the food-selective neurons, the decrement in response was maximal for the first, familiar presentation, and negligible for further presentations.

In clinical tests, the responses of the face-selective neurons to foods were small relative to responses elicited by faces. An example of the results of this clinical testing for one such face-selective neuron is shown in Fig. 9. None of five neurons tested were responsive to an auditory cue that signalled availability of juice. Three of five neurons tested responded weakly to the sound of movements of the laboratory chairs, but were not responsive to the tone cue preceding the presentation of the visual stimuli in the tasks, or to the sound of a line printer that occurred at the

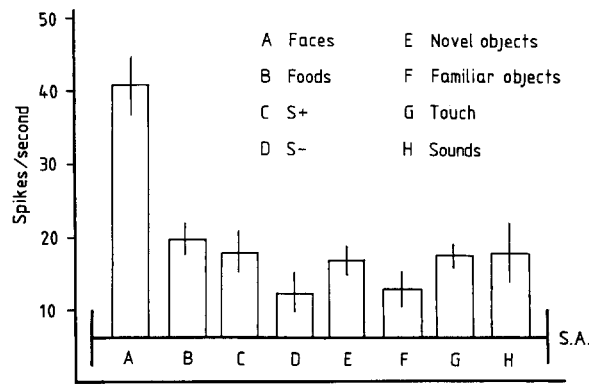

Fig. 9. Responses of a face-selective neuron (305) during the clinical tests. Each *bar* represents the mean response (and standard error of the mean) to different stimulus events. The neuron is maximally responsive to faces, and markedly less responsive to presentations of all other visual, auditory and tactile stimuli. *SA*, spontaneous activity

completion of every trial. Two of four neurons tested responded weakly to manipulation of the monkeys' limbs and torso; these neurons also responded weakly to sounds (e.g. Fig. 9).

Discussion

The present experiments have shown that the responses of one type of amygdaloid neuron distinguish between stimuli on the basis of their novelty, while two other types respond to specific categories of familiar stimuli – foods and faces. We suggest that these properties reflect the operation of memory mechanisms, but, before discussing this proposition, it is necessary to show that other factors do not account for the results.

Methodological issues

There are a number of reasons for excluding changes in arousal, the reinforcement value of the stimuli, changes in attention and vigilance, and eye movements as the bases of the neuronal responses to novel stimuli, to foods and to faces. Firstly, it is probable that all of the stimuli shown in the recognition memory and visual discrimination tasks were arousing for the monkeys. Although it is not possible to equate a particular type of stimulus with a specific level of arousal, we endeavoured to test each neuron for responsiveness to novel and familiar stimuli, foods and faces, and the S+ and S– in the discrimination task. Despite the uniform testing procedure, the three types of neurons responded quite specifically either to novel stimuli, or to foods, or to faces, making it improbable that a single factor such as arousal produced by a particular stimulus could account for the results.

Secondly, although all the stimuli signalled the availability of reinforcement, either juice (S+, familiar stimuli, foods and faces) or saline (S– and novel stimuli), the 3 groups of neurons did not respond to the stimuli on the basis of their reinforcement value. For example, the food-selective neurons were not responsive to the S+ and S–, and this finding indicates that the basis of the neuronal responses is the category (novel, food or face) of the stimulus, rather than the association of the stimulus with reinforcement. In contrast, the responses of a different population of amygdaloid neurons analysed by Sanghera et al. (1979), and by Wilson and Rolls (submitted, see Table 1), do tend to reflect the reinforcement value of visual stimuli.

Thirdly, the experiment was designed so that large sets of stimuli were used on a daily basis in which novel and familiar stimuli, the S+ and S–, foods and faces were presented in pseudorandom order. This diverse range of stimuli enabled us to test the selectivity of individual neurons and allowed us to further establish that these selective responses were specific for foods and faces, extending the observations of Sanghera et al. (1979) and Leonard et al. (1985), and corroborating similar findings in other studies (Jacobs and McGinty 1972; Nishijo et al. 1988; O'Keefe and Bouma 1969). Furthermore, the pseudorandom presentation of the stimuli made it necessary for the monkeys to be consistently attentive, as juice and saline reinforcement was available with a probability of 0.5 on each trial, and thus the monkeys had to make a decision – to respond or not to respond – on every trial, ensuring that attention to the stimulus was obligatory until the decision was made. On most trials the monkeys were unable to predict which stimulus was to be presented. However, in the selected experiments in which multiple, repeated presentations of the same stimulus were made, the latencies of the lick responses often decreased following the repeated appearance of the stimuli, indicating that the monkeys anticipated its appearance and thus were not using visual information to guide their responses, emphasising the need for a pseudorandom presentation sequence.

Fourthly, the time course of the differential neuronal responses to novel and familiar stimuli was rapid, occurring on average 212 ms after the stimulus had appeared, and preceding the behavioural lick responses by 50–150 ms. Furthermore, this differential effect was apparent as soon as the stimulus was shown as familiar, and did not take several presentations to develop. These short-latency, differential neuronal responses make it unlikely that they are due to changes in attention and arousal.

Fifthly, eye movements are also unlikely to be the cause of the differential neuronal responses. Electro-oculographic (EOG) recordings were made in the two monkeys participating in the present experiments; their eye movements were similar on novel and familiar trials over the period in which the neuronal data were recorded (Wilson and Rolls 1990b). In subsequent experiments, in which the duration of gaze of pictures was measured using the scleral search coil technique, four monkeys examined novel stimuli for a mean duration of 2.9 s before looking away from the stimuli, while the examination of the same stimuli presented between no and two intervening trials (6–18 s) later lasted for an average of 2.1 s (Wilson and Goldman-Rakic, submitted). This behavioural study shows that, although eye movements in rhesus monkeys are reliably affected by the familiarity of the stimuli, the time course of the differences in eye movements is much longer than, and cannot account for the short-latency differential neuronal responses to novel and familiar stimuli.

Amygdaloid neuronal activity and the short-term storage of information

The experiments described here show that the responses of one type of amygdaloid neuron distinguish between novel and familiar presentations of the same stimuli, and indicate that this differential activity reflects the temporary storage of information. The differential responses of these neurons were characterised by consistent responses to all novel stimuli, followed by a significant decrement in response at short latencies on the first trial on which the stimulus was seen as familiar. For these novelty-responsive neurons, the decrement in response occurred for all the stimuli tested. Other reports of habituation-like re-

sponses in amygdaloid neurons have been described (Creutzfeldt et al. 1963; Ben-Ari and Le Gal La Salle 1974), and Nishijo et al. (1988) have concluded that most amygdaloid neurons respond vigorously to novel stimuli. However, the present data lead us to place some constraints on this conclusion. Although many non-selective neurons (122/659, Table 1) other than the novelty-responsive neurons responded to the sight of novel visual stimuli, they also responded equally well to the same stimuli when they were shown the next time for their first presentation as familiar. It may be that such visually responsive neurons will eventually cease to respond to a repeatedly presented stimulus, but it is unlikely that this type of slow neuronal habituation carries a signal for novelty that is sufficient to mediate the performance of a recognition memory task, in which monkeys determine and respond to a stimulus on the basis of its novelty or familiarity within 250–400 ms on the first familiar trial on which it is presented.

Furthermore, certain neurons in our sample, which initially appeared to respond on the basis of novelty, were not classified as such, due to the variability of the decremental response and the consequent lack of statistical significance of the effect. In these latter cases the neurons tended to respond selectively to particular stimuli, and decremental effects were restricted to a subset of the presented stimuli, and in these respects are comparable to data reported by Nishijo et al. (1988). It is possible that the firing of these visually responsive neurons reflects the sensory properties of the visual stimuli and/or the habituation of behavioural responses (e.g. eye movements) to the stimuli which occur over a time scale of seconds, as noted above. In the present study the serial recognition task we used made it possible to show that the group of novelty-responsive neurons did not simply habituate to a repeatedly presented stimulus, but instead showed an altered response to the stimulus which reflected a memory for it even when the stimulus had not been seen for 2–10 trials in which other to-be-remembered stimuli were shown. This was defined as the memory span of the neurons. Moreover, the latency of the differential responses of these neurons to novel and familiar stimuli was approximately 200 ms in monkeys who had to look at the stimulus location at the start of the trial in order to solve the task rapidly, and who could not predict what the next stimulus would be.

The properties of amygdaloid neurons responding to novel stimuli can be usefully contrasted with similar and possibly functionally related neuronal groups in the visual association cortices afferent to the amygdala. Visual information may reach the amygdala from several sources: the inferior temporal cortex, the perirhinal cortices, the cortex in the superior temporal sulcus and the temporal pole (Aggleton et al. 1980; Herzog and Van Hoesen 1976; Iwai and Yukie 1987; Turner et al. 1980; Van Hoesen and Pandya 1975). In the lateral inferior temporal cortex, Baylis and Rolls (1987) found that neurons responding to novel stimuli had memory spans limited to a single intervening stimulus. Evidence obtained from recordings in the perirhinal and medial inferior temporal cortices indicates that neuronal activity in these regions may carry information about familiarity for periods of up to 15 min (Brown et al. 1987; Miller et al. 1991; Miyashita and Chang 1988; Riches et al. 1991; Wilson et al. 1988). These comparative data raise the possibility that the amygdala and perirhinal/medial inferior temporal cortices provide the substrate for an information storage mechanism that is more durable than that of lateral inferior temporal cortex. However, neurons in both the perirhinal and inferior temporal cortices tend to be selectively responsive to particular visual stimuli (Baylis and Rolls 1987; Desimone et al. 1984; Riches et al. 1991), whereas the novelty-responsive amygdaloid neurons described above respond to all novel visual stimuli.

Two groups of amygdaloid neurons in this study responded to specific categories of stimuli – foods and faces. We have described similar neurons previously (Sanghera et al. 1979; Leonard et al. 1985). However, in the study described here we measured the responses of these neurons in the serial recognition memory task, and found that the responses of a subset of these stimulus-specific neurons occurred differentially to the first (novel) and second (familiar) presentations of the foods (3/4 neurons tested) and faces (2/6 neurons tested).

This memory-like phenomenon in the three groups of neurons, in which a smaller response to a stimulus occurs with increasing familiarity due to stimulus repetition, seems to be a short-term effect, as the calculated "memory spans" of these neurons were in most cases less than 10 trials. Thus the decremental responses of all three groups of neurons reflect a short-term memory mechanism for the recency of presentation of the stimuli to which they were optimally responsive. It is unlikely that these neurons encode abstract information such as the sequence or order of presentation (first, second, third, etc.), as the differential responses of these neurons are most apparent between the first and second presentation; subsequent presentations of the same stimuli have negligible effects on the neuronal responses.

The present results suggest that certain amygdaloid neurons are influenced by, or are part of a mechanism supporting, the storage of information for recently seen visual stimuli. This is in accordance with the finding that amygdalectomised monkeys are impaired in their ability to discriminate which of two familiar stimuli have most recently been seen in a delayed non-match-to-sample task (Murray and Mishkin 1984), a specific deficit related to the numbers of stimuli used and thus the relative familiarity of (and interference between) the stimuli. Thus, amygdalectomised monkeys are not impaired in performing delayed non-match-to-sample tasks when the stimuli are relatively unfamiliar (i.e. trial unique), but are increasingly impaired in the performance of an object recognition task when the stimuli are highly familiar, the impairment being most severe when the set size consists of two stimuli (Murray and Mishkin 1984). This task could be performed by remembering which of two familiar stimuli was most recently seen. The data obtained in the recognition memory task in the present study indicate that this function might be accomplished by amygdaloid neuronal activity encoding the recency of stimulus presentations.

Stimulus selectivity: a form of longer term memory?

The encoding of recency may be only one of several mechanisms through which the amygdala contributes to the performance of recognition memory tasks. An additional mechanism may be implemented in the responses of stimulus-selective neurons which could, in principle, provide a signal for familiarity. Thus, if a population of stimulus-selective neurons responds only to familiar stimuli that have become salient through experience, the lack of response to novel stimuli is a code for novelty. In effect, neurons that respond selectively to specific stimuli may provide a mechanism for certain forms of long-term memory. This type of mechanism would be required to store information about a very large number of stimuli if it were to provide a general-purpose recognition memory. Alternatively, it is possible that the circuitry of the amygdala is modified only by stimuli that have an outstanding affective value, so that amygdaloid neurons become selectively responsive to these stimuli, forming a representation of specific categories of stimuli for which there is an affective dimension. Furthermore, there is evidence for associatively mediated neuronal plasticity within amygdaloid circuitry that might accomplish such encoding (Clugnet and LeDoux 1990). Numerous electrophysiological studies have shown that stimulus selectivity, which is suggested to reflect a form of neural plasticity, is a property of certain amygdaloid neurons, in that they may respond selectively to stimuli such as foods, faces, sounds and odours (Creutzfeldt et al. 1963; Jacobs and McGinty 1972; Leonard et al. 1985; Nakamura et al. 1992; Nishijo et al. 1988; O'Keefe and Bouma 1969; Sanghera et al. 1979).

A role for the amygdala in affective reactions?

Amygdalectomy disrupts feeding, emotional and social behaviour (Aggleton and Passingham 1981; Horel et al. 1975; Kling 1972) and it seems plausible that the food- and face-selective neurons described in this paper might participate in such behaviours. The basis of this disruption appears to be a deficit in responding appropriately to stimuli that have significant affective value, and it has been proposed that the amygdala participates in the establishment or recognition of the reinforcing or affective attributes of sensory stimuli (Jones and Mishkin 1972; Weiskrantz 1956). A recent formulation of this idea is that the amygdala functions to engage the neural substrates of emotion, and facilitates certain forms of learning by emotional arousal (Aggleton and Mishkin 1986). Thus, it may be that the stimulus-selective neurons are part of the neural mechanisms underlying emotion, in that they are specifically responsive to stimuli that trigger emotional behaviour. Such neurons may facilitate the selection of certain affective responses which may, perhaps through associative learning, become part of the set of cues that guide behaviour in memory tasks.

Stimulus-selective neurons did not constitute a large proportion of responsive neurons in this study (see also Sanghera et al. 1979; Nishijo et al. 1988), but the incidence of such selectivity is relatively great when compared with the absence of neurons responding selectively to foods and faces in the basal forebrain (Wilson and Rolls 1990-a,b,c). There may be several reasons for the low yield of stimulus-selective amygdaloid neurons. Some of these neurons are highly selective and exhibit graded responses to the elements in the class of stimuli to which they are optimally responsive. Indeed, Nakamura et al. (1992) have found that amygdaloid neurons demonstrate stimulus-selectivity when tested with a large set ($n=60$) of stimuli, and it is possible that some of the non-selective or unresponsive neurons recorded in the present study would exhibit stimulus selectivity if tested with larger sets of stimuli. However, it may be difficult to identify such neurons without the appropriate triggering stimulus and thus an infinitely large battery of stimuli. Leonard et al. (1985) specifically examined the responses of amygdaloid neurons to faces; these neurons were found in relatively high proportions in the accessory basal nucleus, and this localisation may be a further reason for the low incidence in the present study as we attempted to uniformly sample the entirety of the amygdala. The face-selective neurons in the present study were located in the dorsomedial amygdala, some in the accessory basal nucleus, indicating some localisation of the type of information processing occurring within the amygdala. This localisation may be related to the finding that partial lesions of the amygdala aimed for the medial sector resulted in temporary difficulties in face recognition in neurosurgical patients (Hitchcock and Cairns 1973; see also Jacobson 1986).

Brain structures involved in recognition memory

A major objective of the present study was to examine the hypothesis that the amygdala contributes to recognition memory by providing a code for familiarity, a function that could be used to support memory-related neuronal activity recorded in the basal forebrain. Two mechanisms have been outlined which could, in principle, provide information about the familiarity of visual stimuli: a code for recency based on short-term storage of information; and a code for novelty/familiarity based on populations of neurons that are selectively responsive to highly familiar, motivationally salient stimuli. In the absence of these mechanisms, it follows that some process intrinsic to the basal forebrain, or intrinsic to its other afferent structures, is responsible for the mnemonic information reflected in the neuronal activity of the basal forebrain. Two groups of basal forebrain neurons had average estimated memory spans exceeding the 16 intervening trials used in the testing, with a third group of neurons demonstrating average memory spans of 9 intervening trials (Rolls et al. 1982; Wilson and Rolls 1990a,b). These latter neurons responded maximally to novel stimuli, as did the amygdaloid neurons described above, a commonality of function which might be expected on the basis of the anatomical similarities between the amygdala and the basal forebrain (Alheid and Heimer 1988).

However, the memory spans of most basal forebrain

neurons are in most cases greater than those of the amygdala, and it appears that either the hypothetical mechanisms outlined above are capable of encoding a signal for familiarity sufficient to support the mnemonic information carried in the responses of basal forebrain neurons, or that other brain structures provide such a signal. Evidence for the latter proposition comes from anatomical studies that have shown that fibres from anterior visual association cortex project to the amygdala, prefrontal cortex, to the medial thalamus and to the basal forebrain (Aggleton et al. 1986; Gower 1989; Jones and Powell 1970; Mesulam and Mufson 1984; Russchen et al. 1985; Wilson and Rolls 1990a). These projections, which are reciprocal, make it possible for visual information to influence the basal forebrain and indeed any of several connected structures through different routes. Consistent with these anatomical findings are lesion and neurophysiological studies that have demonstrated a contribution to recognition memory by the medial temporal cortex surrounding the amygdala and hippocampus (Brown et al. 1987; Horel et al. 1987; Murray and Mishkin 1986; Riches et al. 1991; Wilson et al. 1988, 1990; Zola-Morgan et al. 1989), by the ventromedial prefrontal cortex (Bachevalier and Mishkin 1986), by the basal forebrain (Aigner et al. 1991; Irle and Markowitsch 1987; Rolls et al. 1982; Wilson and Rolls 1990 a,b) and by the medial thalamus (Aggleton and Mishkin 1983; Zola-Morgan and Squire 1989). These studies provide support for the proposal of a system of connected brain structures that contribute to object recognition in the monkey (Mishkin 1982).

At present, it is premature to exclude roles for the hippocampus, the amygdala, or the medial temporal cortex in memory processes. On the contrary, it appears that all three structures have contributory functions. Lesion and neurophysiological studies indicate that the amygdala and hippocampus can be functionally dissociated (for review, see Murray 1990). For example, the hippocampus has a role in memory for behavioural responses (Gaffan 1985; Miyashita et al. 1989; Wilson et al. 1990) and for the spatial location of objects (Parkinson et al. 1988; Rolls et al. 1989; Rolls 1990b), functions that are not affected by damage to the amygdala. In contrast the amygdala, but not the hippocampus, is important for the performance of some, but not all, types of associative learning tasks (Gaffan et al. 1989; Jones and Mishkin 1972; Murray and Mishkin 1984; Spiegler and Mishkin 1981; Squire and Zola-Morgan 1983; Rolls 1990a). With respect to recognition memory, it should be noted that although neuronal activity carrying information about novelty or recency is rare in the amygdala, it is more prevalent than in the hippocampus, where none of 587 hippocampal neurons responded on the basis of novelty or familiarity during the performance of recognition memory and delayed matching tasks (Brown et al. 1987; Riches et al. 1991; Wilson et al. 1990). It is of interest to find that amygdalectomised, but not hippocampectomised, monkeys are impaired in the delayed non-match-to-sample task requiring the discrimination of recency (Murray and Mishkin 1984), which is consistent with the possibility that the novelty-responsive neurons in the amygdala play a role in the performance of short-term object recognition tasks.

One interpretation of these diverse studies is to hypothesise the existence of different, complementary functions carried out within the hippocampus, amygdala and medial temporal cortices and which may each contribute in a unique way to the normal performance of memory tasks, functions that can support task performance to a limited degree in the event of damage to one structure and the loss of its unique functions.

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