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Perirhinal cortex resolves feature ambiguity in complex visual discriminations

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Abstract

The present experiment tested predictions of a 'perceptual–mnemonic/feature conjunction' (PMFC) model of perirhinal cortex function. The model predicts that lesions of perirhinal cortex should disrupt complex visual discriminations with a high degree of 'feature ambiguity', a property of visual discrimination problems that can emerge when features of an object are rewarded when they are part of one object, but not when part of another. As feature ambiguity is thought to be the critical factor, such effects should be independent of the number of objects to be discriminated. This was tested directly, by assessing performance of control monkeys and monkeys with aspiration lesions of perirhinal cortex on a series of concurrent discriminations in which the number of object pairs was held constant, but the degree of feature ambiguity was varied systematically. Monkeys were tested in three conditions: Maximum Feature Ambiguity, in which all features were explicitly ambiguous (AB+, CD+, BC–, AD–; the biconditional problem); Minimum Feature Ambiguity, in which no features were explicitly ambiguous (AB+, CD+, EF–, GH–); and Intermediate Feature Ambiguity, in which half the features were explicitly ambiguous (AB+, CD+, CE–, AF–). The pattern of results closely matched that predicted by simulations using a connectionist network: monkeys with perirhinal cortex lesions were unimpaired in the Minimum Feature Ambiguity condition, mildly impaired in the Intermediate Feature Ambiguity condition and severely impaired in the Maximum Feature Ambiguity condition. These results confirm the predictions of the PMFC model, and force a reconsideration of prevailing views regarding perirhinal cortex function.

Introduction

The perirhinal cortex, a region located at the ventromedial aspect of the primate temporal lobe, lies at the interface of the putative medial temporal lobe memory system and the ventral visual stream or 'what' pathway. It receives inputs from both unimodal sensory areas such as the inferior temporal area TE (vision) and the caudal insula (touch), as well as from multimodal regions including the cingulate cortex and orbital frontal cortex (Friedman *et al*., 1986; Suzuki & Amaral, 1994). Because in monkeys perirhinal cortex receives its heaviest inputs from visual sensory areas (Suzuki & Amaral, 1994), studies of perirhinal cortex function have focused on its putative role in visual learning and memory. For example, it is widely accepted that perirhinal cortex is critical for visual recognition and associative memory (e.g. Meunier *et al*., 1993; Murray *et al*., 1993; Mumby & Pinel, 1994; Higuchi & Miyashita, 1996; Buckley & Gaffan, 1998; Buffalo *et al*., 1999; Bussey *et al*., 1999a; Bussey *et al*., 2000; Gaffan *et al*., 2000). Its potential contribution to visual information processing, however, remains controversial. Indeed, the prevailing 'declarative' view posits that the perirhinal cortex, the hippocampus, and other medial temporal lobe structures operate together in the service of declarative memory, playing little or no role in other functions such as visual analysis or perception (e.g. Buffalo *et al*., 1999; Squire, 1992; Sakai & Miyashita, 1993; Buffalo *et al*., 1998; Buffalo *et al*., 2000).

There are certain findings, however, that are difficult to reconcile with the declarative view (for discussion see the companion paper, Bussey & Saksida, 2002; also Murray & Bussey, 1999). We have therefore suggested that the functional effects of lesions in perirhinal cortex on visual discrimination learning and memory may best be understood by considering the putative hierarchical organization of visual representations in the ventral visual stream (e.g. Desimone & Ungerleider, 1989). This view, referred to here as the 'perceptual–mnemonic/feature conjunction' (PMFC) model, has been formalized in a connectionist network, and has been shown to account for extant data on the effects of perirhinal cortex lesions on visual discrimination learning (Bussey & Saksida, 2002).

Data for which the model can account include the report by Buckley & Gaffan (1997) that monkeys with perirhinal cortex lesions are impaired relative to unoperated control monkeys when learning a large, but not a small, number of concurrent pair-wise visual discriminations. This latter finding is consistent with the idea that perirhinal cortex is important for 'object identification' (Buckley & Gaffan, 1998; Murray *et al*., 1998; Murray & Bussey, 1999; Gaffan *et al*., 2000; Murray *et al*., 2000). According to the PMFC model, however, it is not the number of objects that is the critical factor, but rather the degree of 'feature ambiguity', a property of visual discrimination problems that can emerge when features of an object

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are rewarded when part of one object, but not when part of another (for a more detailed discussion see Bussey & Saksida, 2002). According to this view, perirhinal cortex lesions affect concurrent discrimination of large but not small numbers of object pairs because the former possess greater feature ambiguity: as the number of object pairs to be discriminated becomes larger, the probability increases that a given object feature will be rewarded when part of one object, but unrewarded when part of another.

In the present study this idea was tested directly by assessing the performance of control monkeys and monkeys with aspiration lesions of perirhinal cortex on a series of concurrent discriminations in which the number of object pairs was held constant, but the degree of feature ambiguity was varied systematically. Monkeys were tested in three conditions: Maximum Feature Ambiguity, in which all features were explicitly ambiguous (AB+, CD+, BC–, AD–; the biconditional problem); Minimum Feature Ambiguity, in which no features were explicitly ambiguous (AB+, CD+, EF–, GH–); and Intermediate Feature Ambiguity, in which half the features were explicitly ambiguous (AB+, CD+, CE–, AF–). We predicted that even though the number of object pairs to be discriminated was held constant, perirhinal cortex lesions should have a greater effect on discrimination learning as the degree of feature ambiguity is increased. This prediction and the assumptions of the model were made explicit through simulations using the connectionist network of Bussey & Saksida (2002).

Materials and methods

Subjects

Eight rhesus monkeys (*Macaca mulatta*) were the subjects of the present study. The monkeys were housed individually and were fed a controlled diet of Purina Primate Chow (Purina Mills Inc., St. Louis, MO, USA), supplemented with fruit. Four of these monkeys received aspiration lesions of the perirhinal cortex; the remaining four monkeys were retained as unoperated controls. All monkeys had been trained on a series of visual discrimination problems before entering the present study. The training histories of the monkeys in the two groups were identical. All procedures were approved by the NIMH Animal Care and Use Committee.

Surgery

Bilateral aspiration lesions of the perirhinal cortex ($n = 4$) were performed with sterile procedures under visual control with the aid of an operating microscope. On the day of surgery the monkeys were restrained with an injection of ketamine hydrochloride (10 mg/kg, i.m.) and anaesthetized with isoflurane (1–3%, to effect). They received an intravenous drip of isotonic fluids containing an antibiotic (Cefazolin), and heart rate, respiration rate, body temperature, blood pressure and expired CO_2 were monitored closely throughout the procedure. After draping the animal to establish an aseptic field, a coronal incision was made. The skin and underlying galea were retracted. The zygoma was removed to allow access to the portion of the cranium overlying the ventrolateral surface of the frontal and temporal lobes. Then the temporalis muscle was reflected and a large bone flap was taken, extending rostrally to the orbit, ventrally to the base of the temporal fossa, and caudally to the auditory meatus. The dura was first cut over the frontal and anterior temporal lobes. Using a supraorbital approach, the frontal lobe was gently retracted from the orbit with a brain spoon, the rhinal sulcus was identified, and the rostral part of the perirhinal cortex was removed by subpial aspiration with a small-gauge sucker. This part of the lesion extended along the rostral face of the temporal pole from the lateral sulcus to the floor of the temporal fossa, and included the cortex lining the lateral bank of the rhinal sulcus, together with ≈ 2–3 mm of the cortex lateral to the sulcus. The medial boundary of the lesion was the fundus of the rhinal sulcus. After this part of the removal was completed, the dura was sewn over the frontal lobe, and was cut again over the lateral temporal lobe. The monkey's head was now tilted at an angle of 120° from vertical, thereby allowing a subtemporal approach for ablation of the caudal half of the perirhinal cortex. Mannitol was administered at this time (30%; 30 mL i.v. over 30 min) to reduce brain volume and increase accessibility of the ventromedial cortex, which was retracted from the base of the temporal fossa. The lesion was continued caudally from the first ablation, along the lateral bank of the rhinal sulcus, to include the cortex lining the lateral bank as well as ≈ 2–3 mm of cortex lateral to the sulcus. The medial boundary of the lesion was the fundus of the rhinal sulcus. After the removal was completed, the dura was sewn and the bone flap was repositioned and held in place with Vicryl sutures. Finally, the galea was closed with Vicryl sutures and the skin was closed with surgical steel staples.

Dexamethasone sodium phosphate (0.4 mg/kg, i.m.) and an antibiotic (Di-Trim, 0.1 mL/kg, 24% w/v solution, i.m.; Syntex Animal Health Inc, West Des Moines, IA, USA) were administered for 1 day before surgery and for 1 week after surgery to reduce swelling and to prevent infection, respectively. Monkeys also received acetaminophen (40 mg) or Banamine (flunixin meglumine, 5 mg) as an analgesic for 3 days following surgery.

Lesion assessment using MRI

The location and extent of the perirhinal cortex lesions were evaluated using magnetic resonance (MR) images, obtained at 1-mm intervals from each of the four monkeys. The lesions were plotted from digitized coronal sections from MR scans onto standard sections of a rhesus monkey brain at 1-mm intervals. The volumes of the lesions were then measured using Scion Image software (Scion Corporation, Frederick, MD, USA). When both MR images and traditional Nissl-stained histological material have been available for individual cases, investigators have found good agreement between volumes of medial temporal lobes lesions, including perirhinal cortex lesions, as assessed using the two types of material (Bachevalier & Mishkin, 1994; Bachevalier *et al*., 1999; Liu *et al*., 2000). Although such information is limited, it suggests that MR is likely to provide an accurate estimate of the location and extent of the lesions in our operated monkeys.

The extent of the intended lesion, together with MR images through the lesion in two monkeys, is shown in Fig. 1. Reconstructions of the lesions onto ventral surface views of the brain for all four operated monkeys are shown in Fig. 2. The lesions were generally as intended, with damage to perirhinal cortex averaging 92% (range 79–96%) of the total volume of this region. The monkey with the smallest lesion, case PRh-2, had sparing of the deepest portion of the lateral bank of the rhinal sulcus bilaterally. As for inadvertent damage, there was minimal involvement of entorhinal cortex, area TE and areas TF/TH (von Bonin & Bailey, 1947). In no case did damage exceed 4% of the total volume of these regions.

Simulation methods

Connectionist model

This section provides a brief overview of the connectionist network (see Fig. 3). Details of the network are provided in the companion paper (Bussey & Saksida, 2002).

The connectionist model consists of three layers of continuous units: a 'feature' layer, a 'feature conjunction' layer and an

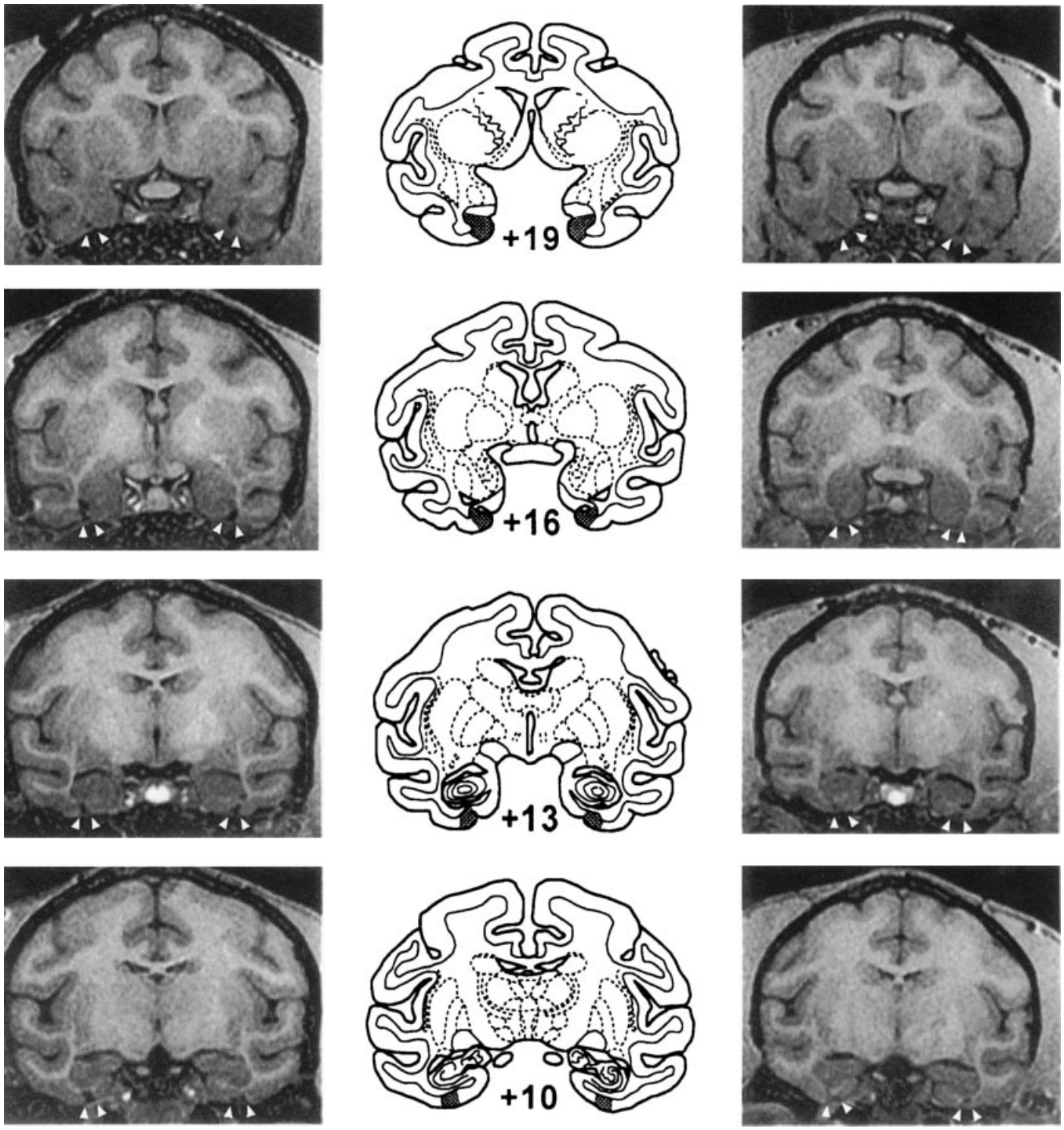

FIG. 1. Extent of the perirhinal cortex lesions in monkeys PRh-1 and PRh-3. The intended lesion (grey) is shown in the central column. Corresponding sections from T1-weighted MR images for each of the two monkeys are shown in columns 1 and 3. The numerals indicate the distance in millimeters from the interaural plane. Arrows indicate the medial and lateral extent of the lesion.

'outcome' node. The feature layer represents cortical regions caudal to perirhinal cortex, the feature conjunction layer represents perirhinal cortex and the outcome node represents the outcome of a trial (reward or nonreward). Upon presentation of a novel stimulus, weights between units in the feature layer and units in the feature conjunction layer are adjusted such that a particular feature conjunction layer unit becomes fully activated each time the stimulus is presented. In addition, upon completion of a trial, weights on the links between active feature layer units and the outcome layer and between active feature conjunction layer units and the outcome layer are adjusted via the Rescorla–Wagner (delta) rule (Rescorla & Wagner, 1972).

Presentation of a stimulus causes 10 units in the feature layer to become activated to a level of 0 or 1. Because of the connections

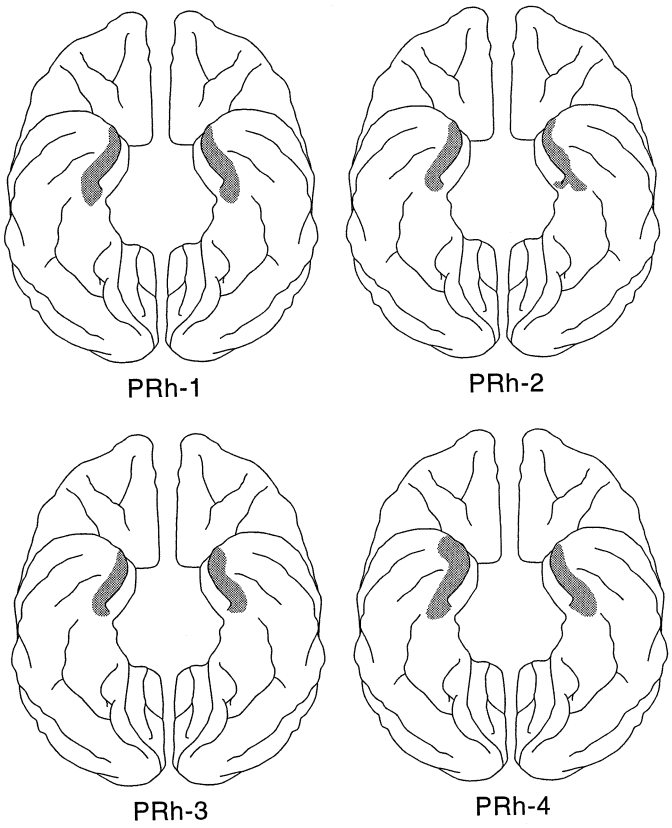

FIG. 2. Ventral views showing the extent of the perirhinal cortex lesions in monkeys PRh-1, PRh-2, PRh-3 and PR-4. Shaded regions indicate the location and extent of the lesion reconstructed from individual sections of the MR images from each of the four operated monkeys. The numerals indicate the distance in millimeters from the interaural plane.

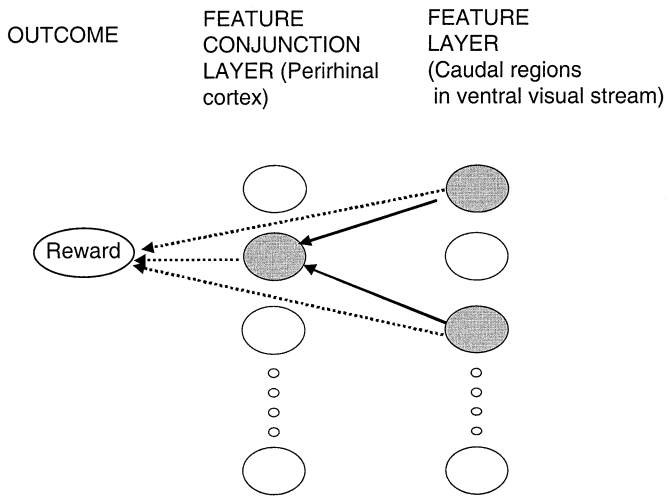

FIG. 3. Diagram of the connectionist network of Bussey & Saksida (2002). The network consists of two layers of units, the feature layer and the feature conjunction layer, as well as an outcome node representing a consequent event (e.g. reward). The feature layer is connected to the feature conjunction layer via a set of fixed weights. Active units are shown in grey. Both the feature layer and the feature conjunction layer are fully connected to the reward node. These weights are adjustable via an associative mechanism. Connections from two units in the feature layer are shown; in fact 10 of the possible 100 units in the feature layer were used to represent a complex photographic stimulus (or 'feature'). The feature conjunction layer represents perirhinal cortex and the feature layer represents more caudal regions of the ventral visual stream. See Bussey & Saksida (2002), for the computational details of the model.

between the feature layer and the feature conjunction layer, activity in the feature layer leads to a pattern of activation on the units in the feature conjunction layer. Any feature conjunction layer unit may be activated by presentation of the stimulus, depending on the similarity of the stimulus to the pattern of weights between the feature layer and the given feature conjunction layer unit. All active feature layer units and feature conjunction layer units become associated with the outcome layer (i.e. the weights on the connections between them increase) to an extent dependent on their degree of activation and whether or not reinforcement occurs. Response probabilities, based on these connection weights, are calculated for the feature layer and for the feature conjunction layer, the former representing the response as predicted by cortical regions caudal to perirhinal cortex and the latter representing the response as predicted by perirhinal cortex.

The monkey experiments in the present study consisted of simultaneous discrimination learning tasks. In this type of task, two two-dimensional 'objects' were presented simultaneously and the monkey had to indicate a choice by selecting one of the two objects. Similarly, in the simulations using the network, on a given simulation trial two stimuli were presented, in this case sequentially, and the network was reinforced for responding to one and not reinforced for responding to the other. For each simulation, two groups of networks were tested. Group Control consisted of intact networks as described above. Group Lesion consisted of networks that had had the feature conjunction layer, representing perirhinal cortex, removed (for details, see Bussey & Saksida, 2002).

Stimuli

Inputs to the network (stimuli) consisted of 100 unit vectors. Units had values of either 1 or 0, representing activation and nonactivation, respectively. The greyscale pictures that were used as 'features' in the behavioural experiment were each represented by the activation of 10 units in the feature layer. Eight of these features were created: A (consisting of units 1–10), B (units 11–20), C (units 21–30), D (units 31–40), E (units 41–50), F (units 51–60), G (units 61–70) and H (units 71–80). The actual stimuli presented to the network, as in the monkey experiment, each consisted of the conjunction of two of the above features. Thus, for each stimulus, 20 units in the feature layer were activated.

Stimuli were presented to the network in a pairwise manner on each trial; one stimulus was designated as the S+ and the other as the S–. Stimuli were arranged into sets, each set consisting of four such stimulus pairs. Networks were tested in three different conditions: Maximum Feature Ambiguity, in which all four features were explicitly ambiguous (AB+, CD+, BC–, AD–; the biconditional problem); Minimum Feature Ambiguity, in which no features were explicitly ambiguous (AB+, CD+, EF–, GH–); and Intermediate Feature Ambiguity, in which two features were explicitly ambiguous (AB+, CD+, CE–, AF–).

Procedure

Two groups of four networks each were initialized (for details, see Bussey & Saksida, 2002): Group 'Control' consisted of intact networks whereas group 'Lesion' consisted of networks with the feature conjunction layer removed to simulate the effect of a lesion in perirhinal cortex. Each network was trained in each of the three

TABLE 1. Object configurations in the three testing conditions

Minimum Feature Ambiguity		Intermediate Feature Ambiguity		Maximum Feature Ambiguity	
+	–	+	–	+	–
A B	E F	***A*** B	***A*** F	***A*** ***B***	***A*** ***D***
A B	G H	***A*** B	***C*** E	***A*** ***B***	***C*** ***B***
C D	E F	***C*** D	***A*** F	***C*** ***D***	***A*** ***D***
C D	G H	***C*** D	***C*** E	***C*** ***D***	***C*** ***B***

Schematic of the object pairs and trial configurations used in the present study. Each capital letter (e.g. A, B) represents a 'feature' and two adjacent features (aligned vertically) comprise an object. Ambiguous features are shown in bold italic. See text for explanation. +, rewarded stimuli; –, unrewarded stimuli. Although the table shows the S+ and S– on the left and right, respectively, in practice the rewarded object could appear on either the left or the right, determined pseudorandomly. Thus the table shows half the available trial configurations. Compare and contrast with Figs 4–6.

feature ambiguity conditions to a criterion of eight correct responses in 10 consecutive trials.

Behavioural methods

Test apparatus and materials

Monkeys were trained and tested in an automated apparatus consisting of an IBM-compatible computer linked to a 15-inch colour monitor fitted with a touch-sensitive screen (Microtouch Systems, Woburn, MA, USA) and an automatic pellet dispenser (BRS/LVE, Laurel, MD, USA). Reward pellets (190 mg banana flavored; Noyes, Lancaster, NH, USA) were delivered via a copper tube into a food cup located directly below the centre of the monitor. During each testing session, the monkey was seated in a primate chair inside a testing cubicle. The monkey's head was ≈ 230 mm from the monitor screen.

Each 'object' consisted of the conjunction of two arbitrary 'features', which were rectangular greyscale pictures ('Masterclips' clip-art; IMSI, San Rafael, CA, USA), each ≈ 4 × 4 cm (see Figs 4–6). Objects were presented in pairs, with one item on the left and one on the right of the monitor screen, set ≈ 8 cm apart from centre to centre. Each stimulus set consisted of four such object pairs.

Testing procedure

Monkeys were tested for the ability to learn to discriminate pairs of two-dimensional objects. In each pair, one object was arbitrarily designated positive (the S+) and the other negative (the S–). On each trial, two objects were presented, one S+ and one S–, and they remained on the screen until the monkey made a response by touching one or the other. Touching the S+ resulted in offset of the stimulus display concomitant with delivery of a reward pellet. Touching the S– resulted in offset of the stimulus display with no reward delivery. A correction procedure was used; following an incorrect response, the trial was repeated using the same stimulus configuration. Whether the S+ was on the right or left on a given trial was determined by a pseudorandom series. There was a 10-s interval between trials. In each test session a stimulus set consisting of four different pairs of objects (i.e. a four-pair concurrent discrimination)

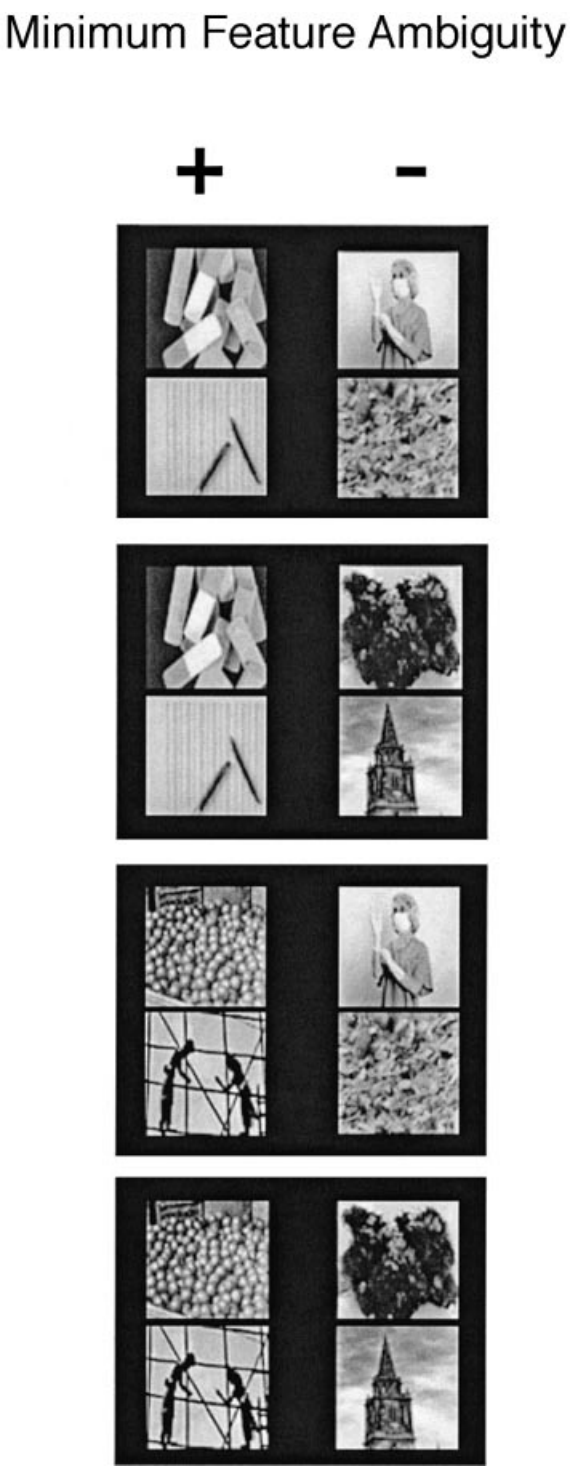

FIG. 4. Example of object pairs in the Minimum Feature Ambiguity condition. Note that in this condition, no features were explicitly ambiguous, i.e. each feature was consistently either rewarded or nonrewarded. The trial configurations in this condition are shown schematically in the first column of Table 1. The features comprising each two-feature object were randomly selected greyscale photographs obtained from a commercially available clip-art collection (see Methods). The + and – indicate that the objects on the left were the correct (rewarded) images in the pair, whereas those on the right were incorrect (unrewarded). In practice, the S+ and S– were presented ≈ 8 cm apart; here they are shown closer together for ease of comparison. For pairs of objects presented in the test sessions, the location of the S+ (left or right) followed a pseudorandom order.

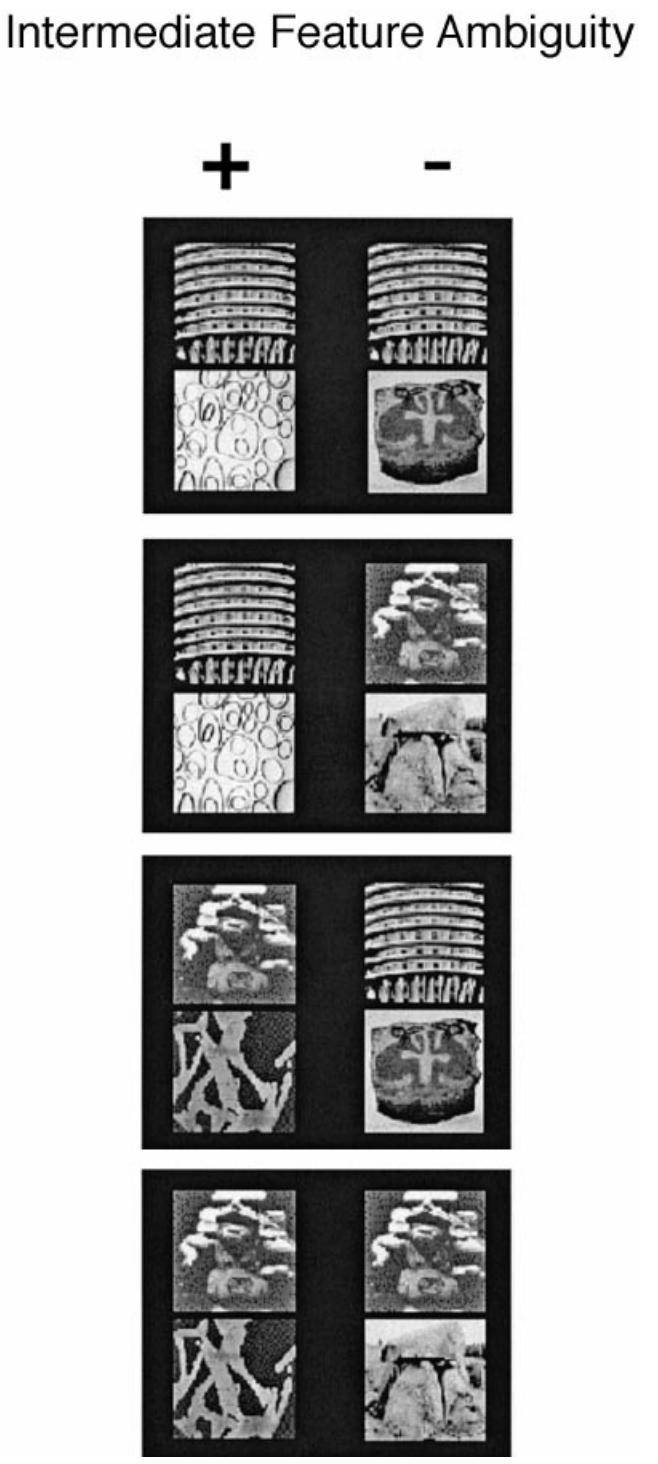

FIG. 5. Example of object pairs in the Intermediate Feature Ambiguity condition. Note that in this condition two features were explicitly ambiguous, i.e. they were rewarded when they appeared as part of one object, but not when part of another. The other features were unambiguous, i.e. they were consistently either rewarded or nonrewarded. The trial configurations in this condition are shown schematically in the second column of Table 1. For additional information see the legend to Fig. 4.

FIG. 6. Example of object pairs in the Maximum Feature Ambiguity condition. Note that in this condition all features were explicitly ambiguous, i.e. they were rewarded when they appeared as part of one object but not when part of another. The trial configurations in this condition are shown schematically in the third column of Table 1. For additional information see the legend to Fig. 4.

was presented for a total of 96 trials. Each pair was presented in 24 trials, plus a variable number of correction trials, in each daily session, and the order in which pairs appeared across trials was determined pseudorandomly. To control for the amount of exposure to the objects, each stimulus set was presented for two consecutive daily sessions (a total of 192 trials), irrespective of whether criterion

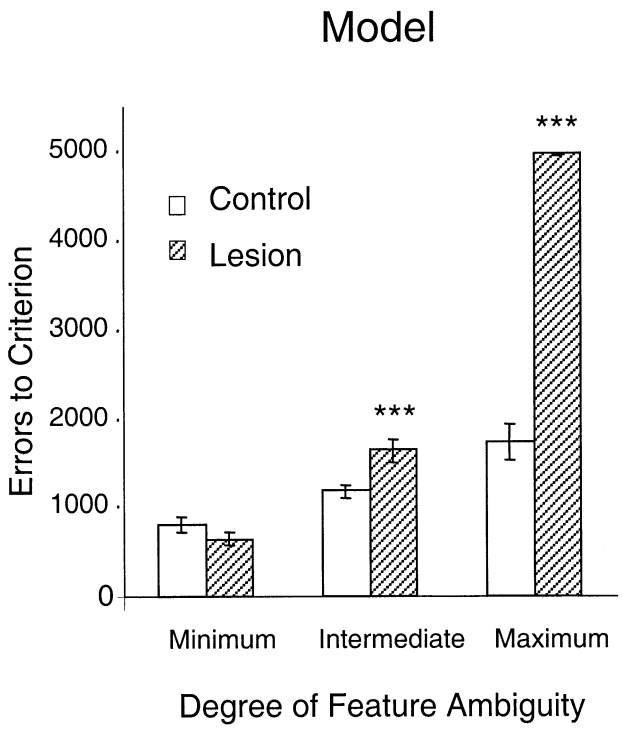

FIG. 7. Simulation data generated by the connectionist network of Bussey & Saksida (2002). Bars indicate the number of errors committed by intact networks and networks with lesions of the feature conjunction layer during acquisition of four-pair concurrent discriminations in each of the Minimum, Intermediate and Maximum Feature Ambiguity conditions. Error bars indicate ± SEM. ***$P < 0.00001$ vs. control. Abbreviations: Control, intact networks ($n = 4$); Lesion, networks with the feature conjunction layer removed ($n = 4$).

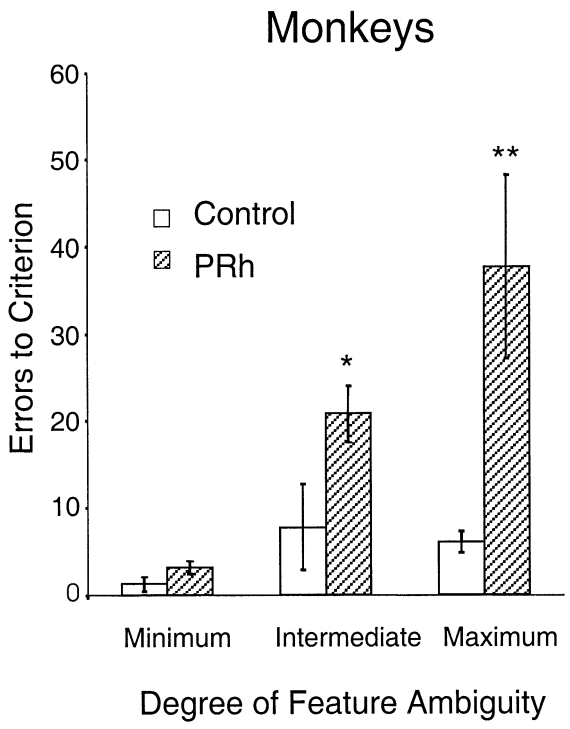

FIG. 8. Acquisition by control monkeys and monkeys with lesions of the perirhinal cortex of four-pair concurrent discriminations in each of the Minimum, Intermediate and Maximum Feature Ambiguity conditions. Scores are the group mean errors to criterion for four sets of problems in each condition. Error bars indicate ± SEM. *$P < 0.05$; **$P = 0.01$ vs. control. Abbreviations: Control, unoperated control monkeys ($n = 4$); PRh, monkeys with bilateral lesions of the perirhinal cortex ($n = 4$).

had been reached. The number of errors committed (not including correction trials) in reaching a criterion of eight correct responses in 10 consecutive trials was recorded. Two monkeys with perirhinal cortex lesions failed to reach criterion on one of the stimulus sets (Maximum Feature Ambiguity condition, see below). In each instance, the total number of errors committed in the two sessions was used as the monkey's score. The same object pairs were used for all monkeys. Monkeys were tested on three different conditions: Maximum Feature Ambiguity, in which all four features were explicitly ambiguous (AB+, CD+, BC–, AD–; the biconditional problem); Minimum Feature Ambiguity, in which no features were explicitly ambiguous (AB+, CD+, EF–, GH–); and Intermediate Feature Ambiguity, in which two features were explicitly ambiguous (AB+, CD+, CE–, AF–). Objects were presented in pairs as shown in Table 1 and Figs 4–6. Which condition was presented in a given pair of sessions was determined by pseudorandom series. Monkeys were tested on four different stimulus sets for each condition, and data were averaged across the four stimulus sets for each condition.

Results

Simulation results

Networks lacking the feature conjunction layer (group 'Lesion') were unimpaired in the Minimum Feature Ambiguity condition, mildly impaired in the Intermediate Feature Ambiguity condition and severely impaired in the Maximum Feature Ambiguity condition (Fig. 7). ANOVA with Group as between-subjects and Condition as within-subjects factors revealed a significant main effect of Group, $F_{1,6} = 748.6$, $P < 0.00001$, a significant main effect of Condition, $F_{2,12} = 561.4$, $P < 0.00001$, and a significant Group × Condition interaction, $F_{2,12} = 294.9$, $P < 0.00001$. Analysis of simple main effects revealed differences between the two groups in the Intermediate ($P < 0.0001$) and Maximum ($P < 0.0001$) conditions, but not in the Minimum condition ($P = 0.13$).

Behavioural results

Monkeys with lesions of the perirhinal cortex were unimpaired in the Minimum Feature Ambiguity condition, mildly impaired in the Intermediate Feature Ambiguity condition and severely impaired in the Maximum Feature Ambiguity condition (Fig. 8). ANOVA with Group as between-subjects and Condition as within-subjects factors revealed a significant main effect of Group, $F_{1,6} = 23.7$, $P = 0.003$, a significant main effect of Condition, $F_{2,12} = 9.78$, $P = 0.003$ and a significant Group × Condition interaction, $F_{2,12} = 5.60$, $P = 0.019$. Analysis of simple main effects revealed differences between the two groups in the Intermediate ($P = 0.04$) and Maximum ($P = 0.01$) conditions, but not in the Minimum condition ($P = 0.11$). Given that, for the Maximum Feature Ambiguity condition, two monkeys with perirhinal cortex lesions failed to attain criterion within the training limit of 192 trials, and therefore the number of errors to criterion for these subjects is underestimated, the magnitude of the effect in this condition may be underestimated as well. Based on the average scores attained on the Maximum Feature Ambiguity condition, there

was no apparent relationship between the size of the lesion and the magnitude of the impairment.

Discussion

The major finding of the present study was that, as the degree of feature ambiguity in a four-pair concurrent discrimination was systematically increased, monkeys with lesions of perirhinal cortex were increasingly impaired. These results suggest that a function of perirhinal cortex is to resolve feature ambiguity in complex visual discriminations.

Buckley & Gaffan (1997) have reported that monkeys with perirhinal cortex lesions can be impaired in concurrent visual discriminations when a large but not a small number of object pairs must be discriminated. This latter finding is consistent with the idea that perirhinal cortex is important for 'object identification' (Buckley & Gaffan, 1998; Murray *et al*., 1998; Murray & Bussey, 1999; Gaffan *et al*., 2000; Murray *et al*., 2000). According to the PMFC model, however, it is not the number of objects that is the critical factor but rather the degree of feature ambiguity. This was tested directly in the present study: the number of items to be discriminated was held constant, and feature ambiguity was manipulated systematically. It was found that as feature ambiguity was increased, monkeys with lesions in perirhinal cortex were increasingly impaired, even though there was no difference in the number of items to be discriminated. In fact, the number of features included in the discrimination was inversely related to the magnitude of the impairment: there were eight features in the Minimum condition, six in the Intermediate condition and only four in the Maximum condition. Thus the results provide strong support for the suggestion that feature ambiguity, and not the number of items to be discriminated, is the critical factor in determining whether monkeys with perirhinal cortex lesions will be impaired on a given visual discrimination problem. This analysis is also consistent with the finding that perirhinal cortex lesions can impair configural learning when the set size is small (Buckley & Gaffan, 1998; Eacott *et al*., 2001)

This analysis provides a possible explanation for the inconsistent findings of experiments investigating the effects of lesions including perirhinal cortex on acquisition of single-pair or concurrent visual discriminations. Some such studies have reported significant impairments (Baxter & Murray, 2001; Buckley & Gaffan, 1997; Buffalo *et al*., 1999) whilst others find no effect (Gaffan & Murray, 1992; Eacott *et al*., 1994; Buckley & Gaffan, 1997; Thornton *et al*., 1997; Buffalo *et al*., 1999; Baxter & Murray, 2001). Because the stimulus material and object set sizes varied considerably across these studies, the amount of feature ambiguity probably varied considerably as well, with the result that perirhinal cortex lesions impaired acquisition in some cases and not others. In the present study stimulus material and set sizes were held constant, and only feature ambiguity varied, revealing a relationship between feature ambiguity and the magnitude of the lesion-induced impairment.

Importantly, the pattern of results in the present study cannot be explained in terms of task difficulty. This is because control monkeys found the discriminations in the Maximum condition no more difficult than those in the Intermediate condition (see Fig. 8), yet monkeys with perirhinal cortex lesions were more severely impaired in the Maximum condition. In addition, in other experiments involving acquisition and performance of single-pair visual discriminations, monkeys with perirhinal cortex lesions were significantly impaired on discriminations with a high degree of feature ambiguity, whereas they were unimpaired on control (colour) discriminations, even though the control and high feature ambiguity discriminations were of equal difficulty (Saksida *et al*., 2000). Consistent with this latter finding, Buckley, Gaffan & Murray (1997) found that monkeys with perirhinal cortex lesions were unimpaired relative to controls on difficult colour discriminations. These experiments provide further support for the idea that feature ambiguity is a critical factor in determining whether perirhinal cortex lesions will impair visual discrimination.

It is perhaps worth noting that, in the present study, features were consistently presented in the same spatial location, to avoid potential confounds related to the requirement of the monkeys to identify a given feature irrespective of the location in which it was presented. For example, inspection of Fig. 5 reveals that in the Intermediate condition the ambiguous features were always at the top of the stimulus and the unambiguous features are always on the bottom. As a result, it is conceivable that monkeys invoked attentional processes to 'tune out' the topmost feature of each stimulus, thus reducing the problem to a low feature ambiguity discrimination. Perhaps, then, monkeys with perirhinal cortex lesions were impaired because they were unable to tune out the ambiguous features. There are several reasons why this explanation is unlikely. First, control monkeys found the Intermediate condition to be just as difficult as the Maximum condition (see Fig. 8), although a 'tuning out' strategy is not possible in the Maximum condition. Second, control monkeys found the Intermediate condition to be more difficult than the Minimum condition, indicating that control monkeys were not able to reduce the Intermediate problem to a Minimum problem by tuning out the ambiguous features. Finally, there is no opportunity for tuning out of ambiguous features in the Maximum condition (as all features are ambiguous in this condition) yet monkeys with perirhinal cortex lesions were severely impaired. For these reasons it seems highly unlikely that the pattern of effects can be explained by an inability of the monkeys with perirhinal cortex lesions to tune out the ambiguous features of the stimuli.

In the present experiment, we used single greyscale pictures as 'features', and combinations of two of these features as 'feature conjunction' stimuli. This choice of stimuli was not arbitrary, but was made because these types of picture stimuli are known to elicit vigorous selective responding from neurons in perirhinal cortex (e.g. Erickson *et al*., 2000). Although it is well accepted that the complexity of response-eliciting stimuli increases from caudal to rostral in the ventral visual pathway (Desimone & Ungerleider, 1989), it is not yet known which are the critical factors that drive neuronal responses in the various cortical fields comprising this pathway (although some progress is being made in this regard: Tanaka, 1993; Logothetis *et al*., 1995; Tsunoda *et al*., 2001). Thus although we hypothesize that representations in the ventral visual stream are organized as a hierarchical system of conjunctive representations of increasing complexity, and predict that perirhinal cortex lesions will disrupt tasks requiring the use of the most complex of these conjunctions, it would be difficult to predict a priori the absolute effects of lesions in other specific cortical fields of the ventral visual stream, until more information regarding the response properties of neurons in these regions becomes available. These effects would, according to our view, depend critically on the complexity of the stimuli. Note that this uncertainty does not render our view untestable. A prediction that follows from our view, for example, is that perirhinal cortex lesions should disrupt 'configural' tasks involving more complex stimuli than those disrupted by lesions in more caudal regions, a prediction that could be tested using stimuli ranging from very simple to very complex. Furthermore, we predict that perirhinal cortex lesions will disrupt performance on discrimin-

ation tasks requiring the use of conjunctive representations of complex stimuli of the type used in the present experiment.

The present study shows that as the degree of feature ambiguity in a visual discrimination was increased, monkeys with lesions of perirhinal cortex were increasingly impaired, and that this effect was independent of the number of items to be discriminated, or the difficulty of the discrimination. These results are consistent with the PMFC model of perirhinal cortex function, based on the idea that the perirhinal cortex can be considered to be a rostral component of the ventral visual stream, which processes and stores representations of visual stimuli (Bussey & Saksida, 2002; also Murray & Bussey, 1999). The perirhinal cortex, according to this view, contains complex conjunctive representations of object features. According to this model the representations in cortical fields of the ventral visual stream are neither exclusively configural nor exclusively elemental (Sutherland & Rudy, 1989); the representations in a given region would be 'configural' only relative to more caudal regions (for additional discussion, see Bussey & Saksida, 2002). Converging evidence in support of this model has been provided by two preliminary studies that have systematically varied feature ambiguity in a different way than in the present study, by morphing (blending) stimuli to achieve different levels of feature ambiguity (Bussey *et al*., 1999b; Saksida *et al*., 2000).

It is important to note that the PMFC model is not intended to provide a complete characterization of perirhinal cortex connectivity and function. Whereas other regions of the ventral visual stream are purely visual, perirhinal cortex has access to nonvisual sensory information. For example, perirhinal cortex receives inputs from both unimodal cortical fields such as TE (vision), the caudal insula (touch) and cortex on the superior temporal gyrus (audition), as well as from multimodal cortical fields such as orbital frontal cortex (for review see box 3 of Murray & Bussey, 1999). It is conceivable that these connections allow the binding of visual and nonvisual features in the service of object identification (Murray & Bussey, 1999; Murray, 2000). In the present study we focus on the role of perirhinal cortex specifically in visual discrimination. Accordingly, our model is based on the properties of perirhinal cortex thought to be shared with other visual areas in the ventral visual stream. How our model fits into a more comprehensive theory of perirhinal cortex function encompassing, for example, object recognition and intramodal and crossmodal associative learning and memory, is a target for future research.

Finally, the perirhinal cortex lesions in the present study were made using the aspiration method. Given that excitotoxic lesions of the perirhinal or rhinal cortex have been found to produce much the same effect as aspiration lesions (Baxter & Murray, 2001; Malkova *et al*., 2001), including effects on discrimination learning (Baxter & Murray, 2001), it seems likely that the behavioural effects of our lesions are due to cell loss in the perirhinal cortex. Nevertheless, we cannot rule out the possibility that disruption of fibres of passage, rather than of perirhinal cortex neurons *per se*, is responsible for the impairments we have observed. Future studies will need to address this possibility.

Conclusions

The pattern of results from the present study, and from the work of, for example, Gaffan and colleagues, forces a reconsideration of the role of perirhinal cortex in visual perception and memory. Perirhinal cortex lesions result in impairments on visual discrimination tasks that can be construed either as mnemonic, requiring the memory for visual stimuli, or perceptual, requiring accurate discrimination of visual stimuli. According to our view, the underlying cause of these impairments may be one and the same: lesions in this region compromise the representation of visual stimuli, and both accurate perception and accurate memory require accurate representation. Thus we propose, contrary to prevailing views, that 'perceptual' and 'mnemonic' functions are unlikely to be neatly organized into anatomically segregated modules in the brain.

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Abbreviations

MR, magnetic resonance; PMFC, perceptual–mnemonic/feature conjunction.

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