

MEMORY SYSTEMS IN THE BRAIN

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■ **Abstract** The operation of different brain systems involved in different types of memory is described. One is a system in the primate orbitofrontal cortex and amygdala involved in representing rewards and punishers, and in learning stimulus-reinforcer associations. This system is involved in emotion and motivation. A second system in the temporal cortical visual areas is involved in learning invariant representations of objects. A third system in the hippocampus is implicated in episodic memory and in spatial function. Fourth, brain systems in the frontal and temporal cortices involved in short term memory are described. The approach taken provides insight into the neuronal operations that take place in each of these brain systems, and has the aim of leading to quantitative biologically plausible neuronal network models of how each of these memory systems actually operates.

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INTRODUCTION

Neuroscience has reached the stage where it is possible to understand how parts of the brain actually work, by combining approaches from many disciplines. Evidence on the connections and internal connectivity of each brain region, of the biophysical properties of single neurons (Koch 1999), on what is represented by neuronal activity in each brain region, and on the effects of lesions, all provide the foundation for a computational understanding of brain function in terms of the neuronal network operations being performed in each region (Rolls & Treves 1998). Crucial brain systems to understand are those involved in memory, but in addition, learning mechanisms are at the heart of how the brain processes information, for it is by modifying the synaptic connection strengths (or weights) between neurons that useful neuronal information processors for most brain functions, including perception, emotion, motivation, and motor function, are built. The application of this approach to understanding not only what functions are performed, but also how they are performed, is described here for a number of different brain systems.

A major reason for investigating the actual brain mechanisms that underlie behavior is not only to understand how our own brains work, but also to have the basis for understanding and treating medical disorders of the brain. Because of the intended relevance to humans, emphasis is placed here on research in nonhuman primates. This is important because many brain systems, including systems in the temporal lobes and the prefrontal cortex, have undergone considerable development in primates. The elaboration of some of these brain areas has been so great in primates that even evolutionarily old systems such as the taste system appear to have been reconnected (compared to rodents) to place much more emphasis on cortical processing taking place in areas such as the orbitofrontal cortex. In primates, there has also been great development of the visual system, and this itself has had important implications not only for perceptual but also for memory and emotional systems in the brain.

REPRESENTATIONS OF REWARDS AND PUNISHERS; LEARNING ABOUT STIMULI ASSOCIATED WITH REWARDS AND PUNISHERS; EMOTION AND MOTIVATION

Brain systems involved in rewards and punishers are important not only because they are involved in emotion and motivation, but also because they are important in understanding many aspects of brain design, including what signals should be decoded by sensory systems, how learning about the stimuli that are associated with rewards and punishers occurs, and how action systems in the brain must be built (Rolls 1999a). These ideas are introduced next.

Emotions can usefully be defined as states elicited by rewards and punishers (Rolls 1990, 1999a, 2000a). A reward is anything for which an animal will work. A punisher is anything an animal will work to escape or avoid. An example of an emotion might thus be happiness produced by being given a reward, such as a pleasant touch, praise, or winning a large sum of money; another example is fear produced by the sight of a painful stimulus. Frustration, anger, or sadness can be produced by the omission of an expected reward or the termination of a reward, such as the death of a loved one. In contrast, relief can be produced by the omission or termination of a punishing stimulus, such as the removal of a painful stimulus. These examples indicate how emotions can be produced by the delivery, omission, or termination of rewarding or punishing stimuli, and go some way to indicate how different emotions could be produced and classified in terms of the rewards and punishments received, omitted, or terminated (Rolls 1999a).

Rewards and punishers can be more formally defined as instrumental reinforcers, i.e. stimuli or events which, if their occurrence, termination, or omission is made contingent upon the making of a response, alter the probability of the future emission of that response. Some stimuli are unlearned, or primary, reinforcers (e.g. pain or the taste of food if the animal is hungry), whereas others may become reinforcing by learning, through their association with primary reinforcers, thereby becoming secondary reinforcers. This type of learning may thus be called stimulus-reinforcement association learning. For example, fear is an emotional state that might be produced by a sound (the conditioned stimulus) that has previously been associated with a painful stimulus (the primary reinforcer).

Part of the adaptive value of emotional (and motivational) states is to allow a simple interface between sensory inputs and action systems (Rolls 1999a). The essence of this idea is that goals for behavior are specified by reward and punishment evaluation. When an environmental stimulus has been decoded as a primary reward or punishment, or (after previous stimulus-reinforcer association learning) as a secondary rewarding or punishing stimulus, then it becomes a goal for action. The animal can then perform any action (instrumental response) to obtain the reward, or to avoid the punisher. Thus, there is flexibility of action, and this is in contrast with stimulus-response, or habit, learning, in which a particular response to a particular stimulus is learned. The emotional route to action is flexible not only because any action can be performed to obtain the reward or avoid the punishment, but also because the animal can learn in as little as one trial that a reward or punishment is associated with a particular stimulus by stimulus-reinforcer association learning. Animals must be built during evolution to be motivated to obtain certain rewards and avoid certain punishers. Indeed, primary, or unlearned, rewards and punishers are specified by genes that effectively specify the goals for action. Rolls (1999a) proposes that this is the solution that natural selection has found for how genes can influence behavior to promote their fitness (as measured by reproductive success), and for how the brain could flexibly interface sensory systems with action systems.

We now turn to address the brain mechanisms that implement these processes, by considering where primary rewards and punishers are represented in the brain, which parts of the brain are involved in learning associations of stimuli to rewards and punishers, and how they do this. Some of the pathways described here are shown on a lateral view of a primate brain in Figure 1 and schematically in Figure 2.

Representation of Primary (Unlearned) Rewards and Punishers

For primary reinforcers, the reward decoding may occur only after several stages of processing, as in the primate taste system, in which reward is decoded only after the primary taste cortex. By decoding, I mean making explicit some aspect of the stimulus or event in the firing of neurons. A decoded representation is one in which the information can be read easily, for example by taking a sum of the synaptically weighted firing of a population of neurons (Rolls & Treves 1998). Processing as far as the primary taste cortex (Figure 2) represents what the taste is, whereas in the secondary taste cortex, in the orbitofrontal cortex, the reward value of taste is represented. This is shown by the fact that when the reward value of the taste of food is decreased by feeding it to satiety, the responses of neurons in the orbitofrontal cortex, but not at earlier stages of processing in primates, decrease to the food as the reward value of the food decreases (Rolls 1997a, 1999a). This functional architecture enables the taste representation in the primary cortex to be used for purposes that are not reward dependent. One example might be learning where a particular taste can be found in the environment, even when the taste is not pleasant because the primate is not hungry. The representation of taste reward in the primate orbitofrontal cortex is very rich, in that there are ensemble encoded representations of sweet, salt, bitter, sour, and umami (protein taste, exemplified by glutamate) tastes, with the neuronal representation of each well separated, as shown by multidimensional scaling (Rolls 1997a). Moreover, this representation is supplemented by representations of astringency (Critchley & Rolls 1996c) (important for detecting tannin-like substances in foods, which impair the absorption of protein), and of the fat content of food (Rolls et al 1999a), both of which activate orbitofrontal cortex neurons through the somatosensory pathways. The representation of reward in the orbitofrontal cortex is made much richer even than this, by incorporating olfactory information to build by olfactory-to-taste learning (see below) representations of the flavor of food, and by also incorporating visual information about food using visual-to-taste association learning (see below). Further evidence that this is a reward mechanism for food is that electrical brain-stimulation reward occurs in this region of the orbitofrontal cortex and is hunger dependent (Rolls 1999a), and that lesions of the orbitofrontal cortex lead to much less discriminating selection of foods and other items to eat (Baylis & Gaffan 1991).

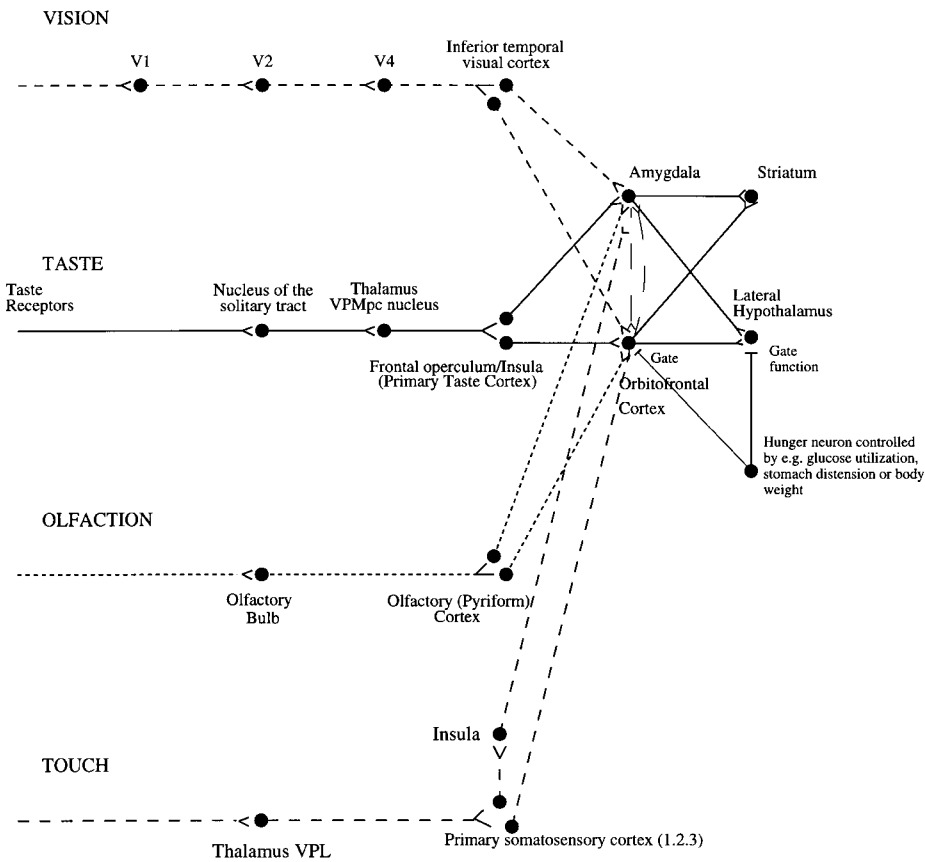


Figure 2 Diagrammatic representation of some of the connections described in the text. V1, striate visual cortex; V2 and V4, cortical visual areas. In primates, sensory analysis proceeds in the visual system as far as the inferior temporal cortex and the primary gustatory cortex; beyond these areas, for example in the amygdala and orbitofrontal cortex, the hedonic value of the stimuli, and whether they are reinforcing or are associated with reinforcement, is represented (see text). The gate function refers to the fact that in the orbitofrontal cortex and hypothalamus the responses of neurons to food are modulated by hunger signals. (After Rolls 1999a: Figure 4.2)

A principle that assists the selection of different behaviors is sensory-specific satiety, which builds up when a reward is repeated for a number of minutes. An example is sensory-specific satiety for the flavor of food, whereby if one food is eaten to satiety and becomes no longer rewarding, other foods may still remain rewarding and be eaten (Rolls 1997a, 1999a). The mechanism for this is implemented in the primate orbitofrontal cortex, in that sensory-specific satiety mirrors the sensory-specific decrease in orbitofrontal neuronal responses to a food that is

being fed to satiety (Critchley & Rolls 1996a, Rolls et al 1989), and no decrease is found at earlier stages of processing in the primary taste cortex (Rolls et al 1988) or inferior temporal visual cortex (Rolls et al 1977). The neurophysiological basis proposed for this is in part a type of learning involving habituation with a time course of several minutes of stimulation at the orbitofrontal stage of processing (where reward is represented), but not at earlier stages of processing (where sensory-specific satiety does not modulate neuronal responses) (Rolls et al 1989c, 1999a).

Another primary reinforcer, the pleasantness of touch, is represented in another part of the orbitofrontal cortex, as shown by observations that the orbitofrontal cortex is much more activated (measured with functional magnetic resonance imaging, fMRI) by pleasant relative to neutral touch than is the primary somatosensory cortex (Francis et al 1999). Although pain may be decoded early in sensory processing, in that it utilizes special receptors and pathways, some of the affective aspects of this primary negative reinforcer are represented in the orbitofrontal cortex, in that damage to this region reduces some of the affective aspects of pain in humans (Rolls 1999a), and painful stimuli activate parts of the human orbitofrontal cortex (ET Rolls, J O'Doherty, S Francis, F McGlone, R Bowtell, in preparation).

From the orbitofrontal cortex there are connections to the amygdala and lateral hypothalamus, in both of which there are neurons that respond to reinforcers such as the taste of food. The hypothalamic neurons only respond to the taste of food if the monkey is hungry, and indeed reflect sensory-specific satiety, thus representing the reward value (Rolls 1999a). The evidence on modulation by hunger is less clear for amygdala neurons (Rolls 2000b). There is a connected network in these areas concerned with reward in primates, in that at each site (orbitofrontal cortex, lateral hypothalamus/substantia innominata, and amygdala), electrical stimulation is rewarding, and in that in each site neurons are activated within a few ms by brain-stimulation reward of the other sites, and in many cases also by food reward (Rolls et al 1980).

The Representation of Potential Secondary (Learned) Reinforcers

For potential secondary reinforcers (such as the sight of a particular object or person) in primates, analysis generally proceeds to the level of invariant object representation before reward and punishment associations are learned. For vision, this level of processing is the inferior temporal visual cortical areas, where there are view-, size-, and position-invariant representations of objects and faces that are not affected by the reward or punishment association of visual stimuli (Rolls 1999a, Gross 1992, Wallis & Rolls 1997, Booth & Rolls 1998, Rolls et al 1977). The utility of invariant representations is to enable correct generalization to other transforms (e.g. views, sizes) of the same or similar objects, even when a reward

or punishment has previously been associated with one instance. The representation of the object is (appropriately) in a form that is ideal as an input to pattern associators, which allow the reinforcement associations to be learned. The representations are appropriately encoded, in that they can be decoded in a neuronally plausible way (e.g. using a synaptically weighted sum of the firing rates); they are distributed so allowing excellent generalization and graceful degradation; and they have relatively independent information conveyed by different neurons in the ensemble, providing high capacity and allowing the information to be read off quickly, in periods of 20–50 ms (Rolls et al 1997b,c; Rolls & Treves 1998; Rolls 1999a). The utility of representations of objects that are independent of reward associations (for vision, in the inferior temporal cortex) is that they can be projected to different neural systems and then used for many functions independently of the motivational or emotional state. These functions include recognition, recall, forming new memories of objects, episodic memory (e.g. to learn where a food is located, even if one is not hungry for the food at present), and short term memory (Rolls & Treves 1998).

In nonprimates, including for example, rodents, the design principles may involve less sophisticated features because the stimuli being processed are simpler. For example, view-invariant object recognition is probably much less developed in nonprimates, and the recognition that is possible is based more on physical similarity in terms of texture, color, simple features, etc (Rolls & Treves 1998:Sect. 8.8). It may be because there is less sophisticated cortical processing of visual stimuli in this way that other sensory systems are also organized more simply, for example with some (but not total, only perhaps 30%) modulation of taste processing by hunger early in sensory processing in rodents (Scott et al 1995). Moreover, although it is usually appropriate to have emotional responses to well-processed objects (e.g. the sight of a particular person), there are instances, such as a loud noise or a pure tone associated with punishment, in which it may be possible to tap off a sensory representation early in sensory processing that can be used to produce emotional responses. This may occur in rodents, in which the subcortical auditory system provides afferents to the amygdala (LeDoux 1992, 1995; Rolls 1999a).

Especially in primates, it may be important to keep track of the reinforcers received from many different individuals in a social group. To provide the input to such reinforcement-association learning mechanisms, there are many neurons devoted to providing an invariant representation of face identity in macaque cortical areas TEa and TEm in the ventral lip of the anterior part of the superior temporal sulcus. In addition, there is a separate system that encodes facial gesture, movement, and view, as all are important in social behavior, for interpreting whether specific individuals, with their own reinforcement associations, are producing threats or appeasements. In macaques many of these neurons are found in the cortex in the depths of the anterior part of the superior temporal sulcus (Baylis et al 1987; Hasselmo et al 1989a,b; Rolls 1997c; Wallis & Rolls 1997).

Stimulus-Reinforcement Association Learning

After mainly unimodal processing to the object level, sensory systems then project into convergence zones. Those especially important for reward, punishment, emotion, and motivation are the orbitofrontal cortex and amygdala, where primary reinforcers are represented. Pattern associations between potential secondary and primary reinforcers are learned in these brain regions. They are thus the parts of the brain involved in learning the emotional and motivational value of stimuli. Progress on understanding the operation of these systems is considered next.

The Amygdala Some of the connections of the primate amygdala are shown in Figures 1 and 2 (see also Amaral et al 1992, Rolls 1999a). Not only does the amygdala receive information about primary reinforcers (such as taste and touch), but it also receives inputs about stimuli (e.g. visual ones) that can be associated by learning with primary reinforcers. In primates such inputs come mainly from the ends of cortical processing streams for each modality; for example, for vision the inferior temporal cortex and the cortex in the superior temporal sulcus, and for audition the superior temporal auditory association cortex.

Recordings from single neurons in the amygdala of the monkey have shown that some neurons do respond to visual stimuli, with latencies somewhat longer than those of neurons in the temporal cortical visual areas. Some of these neurons respond primarily to reward-related visual stimuli (e.g. in a visual discrimination task to a triangle that signifies a taste reward can be obtained), and some others respond primarily to visual stimuli associated with punishment (e.g. with the taste of saline) (Sanghera et al 1979, Wilson & Rolls 1993, Ono & Nishijo 1992, Rolls 2000b, FAW Wilson & ET Rolls, in preparation). Although the responses of such neurons reflect previously learned reward or punishment associations of visual stimuli, it is not clear that they reverse their responses rapidly (i.e. in a few trials) when the visual discrimination is reversed (Sanghera et al 1979, Rolls 2000b, Ono & Nishijo 1992). The crucial site of the stimulus-reinforcement association learning that underlies the responses of amygdala neurons to learned reinforcing stimuli is probably within the amygdala itself, and not at earlier stages of processing, because neurons in the inferior temporal cortical visual areas do not reflect the reward associations of visual stimuli, but respond to visual stimuli based on their physical characteristics (see above). Association learning in the amygdala may be implemented by associatively modifiable synapses (Rolls & Treves 1998) from visual and auditory neurons onto neurons receiving inputs from taste, olfactory, or somatosensory primary reinforcers. Consistent with this, Davis (1994, Davis et al 1994) has found in the rat that at least one type of associative learning in the amygdala can be blocked by local application to the amygdala of an NMDA (n-methyl-d-aspartate) receptor blocker, which blocks long-term potentiation (LTP), a model of the synaptic changes that underlie learning (Rolls & Treves 1998). Further, evidence that the learned-incentive (conditioned reinforcing) effects of previously neutral stimuli paired with rewards are

mediated by the amygdala acting through the ventral striatum, is that amphetamine injections into the ventral striatum enhanced the effects of a conditioned reinforcing stimulus only if the amygdala was intact (Everitt & Robbins 1992, Everitt et al 2000). The lesion evidence in primates is also consistent with a function of the amygdala in reward- and punishment-related learning, for amygdala lesions in monkeys produce tameness, a lack of emotional responsiveness, excessive examination of objects, often with the mouth, and eating of previously rejected items such as meat (Rolls 1999a). There is evidence that amygdala neurons are involved in these processes in primates, for amygdala lesions made with ibotenic acid impair the processing of reward-related stimuli, in that when the reward value of a set of foods was decreased by feeding it to satiety (i.e. sensory-specific satiety), monkeys still chose the visual stimuli associated with the foods with which they had been satiated (Malkova et al 1997; see further Rolls 2000a).

Further evidence that the primate amygdala processes visual stimuli derived from high-order cortical areas and is of importance in emotional and social behavior is that a population of amygdala neurons has been described that responds primarily to faces (Leonard et al 1985). Each of these neurons responds to some but not all of a set of faces, and thus across an ensemble conveys information about the identity of the face. These neurons are found especially in the basal accessory nucleus of the amygdala, a part of the amygdala that develops markedly in primates (Amaral et al 1992). This part of the amygdala receives inputs from the temporal cortical visual areas in which populations of neurons respond to the identity of faces and to facial expression. This is probably part of a system that has evolved for the rapid and reliable identification of individuals from their faces, and of facial expressions, because of their importance in primate social behavior.

LeDoux and colleagues (1992, 1995, 1996) have traced a system from the medial geniculate directly to the amygdala in rats and have shown that there are associative synaptic modifications in this pathway when pure tones are associated with footshock. The learned responses include typical classically conditioned responses such as heart-rate changes and freezing to fear-inducing stimuli (LeDoux 1995), and also operant responses (Gallagher & Holland 1994). In another type of paradigm, it has been shown that amygdala lesions impair the devaluing effect of pairing a food reward with (aversive) lithium chloride, in that amygdala lesions reduced the classically conditioned responses of the rats to a light previously paired with the food (Hatfield et al 1996; see further Everitt et al 2000). However, the subcortical pathway in which learning occurs, studied by LeDoux and colleagues (see LeDoux 1995), though interesting to study as a model system, is unlikely to be the normal pathway used for reward- and punishment-association learning in primates, in which a visual stimulus will normally need to be analyzed to the object level (to the level e.g. of face identity, which requires cortical processing) before the representation is appropriate for input to a stimulus-reinforcement evaluation system such as the amygdala or orbitofrontal cortex. Similarly, it is typically to complex auditory stimuli (such as a particular person's voice, perhaps making a particular statement) that emo-

tional responses are elicited. The point here is that emotional and motivational responses are usually elicited to environmental stimuli analyzed to the object level (including other organisms), and not to retinal arrays of spots or pure tones. Thus, cortical processing to the object level is required in most normal emotional situations, and these cortical object representations are projected to reach multimodal areas such as the amygdala and orbitofrontal cortex, where the reinforcement label is attached using stimulus-reinforcer pattern-association learning to the primary reinforcers represented in these areas.

Some amygdala neurons that respond to rewarding visual stimuli also respond to relatively novel visual stimuli and they may implement the reward value that novel stimuli have (FAW Wilson & ET Rolls, in preparation; Rolls 1999a, 2000b).

The outputs of the amygdala (Amaral et al 1992) include projections to the hypothalamus and also directly to the autonomic centers in the medulla oblongata, providing one route for cortically processed signals to reach the brainstem and produce autonomic responses. Another interesting output of the amygdala is to the ventral striatum, including the nucleus accumbens, because via this route information processed in the amygdala could gain access to the basal ganglia and thus influence motor output (see Figure 2; Everitt & Robbins 1992). Neurons with reward- and punishment-related responses have been found in the primate nucleus accumbens and other parts of the ventral striatum (Rolls & Williams 1987, Williams et al 1993, Schultz et al 1992). In addition, mood states could affect cognitive processing via the amygdala's direct backprojections to many areas of the temporal, orbitofrontal, and insular cortices from which it receives inputs (Rolls & Treves 1998). Cortical arousal may be produced by conditioned stimuli via the central nucleus of the amygdala outputs to the cholinergic basal forebrain magnocellular nuclei of Meynert (see Kapp et al 1992; Wilson & Rolls 1990a,b,c; Rolls & Treves 1998; Rolls 1999a:Ch. 7). Not only are different amygdala output pathways involved in different responses (broadly instrumental, autonomic, and neuroendocrine effects of conditioned reinforcers), but also there is some specialization within the amygdala for subsystems involved in these different responses (see Everitt et al 2000).

The role of the amygdala in implementing behavior to the reinforcing value of facial expressions has been investigated. Extending the findings on neurons in the macaque amygdala that responded selectively for faces and social interactions (Leonard et al 1985, Brothers & Ring 1993), Young et al (1995, 1996) have described a patient with bilateral damage or disconnection of the amygdala who was impaired in matching and identifying facial expression but not facial identity. Adolphs et al (1994) also found facial expression but not facial identity impairments in a patient with bilateral damage to the amygdala. Although in studies of the effects of amygdala damage in humans, greater impairments have been reported with facial or vocal expressions of fear than with some other expressions (Adolphs et al 1994, Scott et al 1997), and in functional brain imaging studies greater activation may be found with certain classes of emotion-provoking stimuli (e.g. those that induce fear rather than happiness) (Morris et al 1996), it has been

suggested (Rolls 1999a) that it is unlikely that the amygdala is specialized for the decoding of only certain classes of emotional stimuli, such as those that produce fear. This emphasis on fear may be related to the research in rats on the role of the amygdala in fear conditioning (LeDoux 1992, 1995, 1996). Indeed, it is clear from single-neuron studies in nonhuman primates that some amygdala neurons are activated by rewarding stimuli, some by punishing stimuli (see above), and others by a wide range of different face stimuli (Leonard et al 1985). Moreover, lesions of the macaque amygdala impair the learning of both stimulus-reward and stimulus-punisher associations, though there is a need for further research with neurotoxic lesions of the amygdala and the learning of an association between a visual stimulus and a primary reinforcer such as taste (Rolls 2000a). Further, electrical stimulation of the macaque and human amygdala at some sites is rewarding, and humans report pleasure from stimulation at such sites (Rolls 1975, Rolls et al 1980, Sem-Jacobsen 1976, Halgren 1992). Thus, any differences in the magnitude of effects between different classes of emotional stimuli that appear in human functional brain-imaging studies (Morris et al 1996, Davidson & Irwin 1999) or even after amygdala damage (Adolphs et al 1994, Scott et al 1997) should not be taken to show that the human amygdala is involved in only some emotions. Indeed, in current fMRI studies we are finding that the human amygdala is activated perfectly well by the pleasant taste of a sweet (glucose) solution (in the continuation of studies reported by Francis et al 1999), showing that reward-related primary reinforcers do activate the human amygdala.

The Orbitofrontal Cortex The orbitofrontal cortex receives inputs about potential secondary reinforcers, such as olfactory and visual stimuli, as well as about primary reinforcers (see Figures 1 and 2). Some neurons in the orbitofrontal cortex, which contains the secondary and tertiary taste and olfactory cortical areas, respond to the reward value of olfactory stimuli, in that they respond to the odor of food only when the monkey is hungry (Critchley & Rolls 1996b). Moreover, sensory-specific satiety for the reward of the odor of food is represented in the orbitofrontal cortex (Critchley & Rolls 1996b). In addition, some orbitofrontal cortex neurons combine taste and olfactory inputs to represent flavor (Rolls & Baylis 1994), and the principle by which this flavor representation is formed is by olfactory-to-taste association learning (Rolls et al 1996).

The primate orbitofrontal cortex also receives inputs from the inferior temporal visual cortex, and is involved in visual stimulus-reinforcer association learning: Neurons in the orbitofrontal cortex learn visual stimulus-to-taste reinforcer associations in as little as one trial. Moreover, and consistent with the effects of damage to the orbitofrontal cortex that impair performance on visual discrimination reversal, Go/NoGo tasks, and extinction tasks (in which the lesioned macaques continue to make behavioral responses to previously rewarded stimuli), orbitofrontal cortex neurons reverse visual stimulus-reinforcer associations in as little as one trial (Thorpe et al 1983, Rolls et al 1996). Also, a separate population of orbitofrontal cortex neurons responds only on nonreward trials (Thorpe et al

1983). There is thus the basis in the orbitofrontal cortex for rapid learning and updating by relearning or reversing stimulus-reinforcer (sensory-sensory, e.g. visual to taste) associations. In the rapidity of its relearning/reversal, the primate orbitofrontal cortex may effectively replace and perform better some of the functions performed by the amygdala. In addition, some visual neurons in the primate orbitofrontal cortex respond to the sight of faces. These neurons are likely to be involved in learning which emotional responses are currently appropriate to particular individuals, in keeping track of the reinforcers received from each individual, and in making appropriate emotional responses given the facial expression (Rolls 1996a, 1999a).

The evidence thus indicates that the primate orbitofrontal cortex is involved in the evaluation of primary reinforcers, and also implements a mechanism that evaluates whether a reward is expected and generates a mismatch (evident as a firing of the nonreward neurons) if reward is not obtained when expected. These neuronal responses provide further evidence that the orbitofrontal cortex is involved in emotional responses, particularly when these involve correcting previously learned reinforcement contingencies in situations that include those usually described as involving frustration.

It is of interest and potential clinical importance that a number of the symptoms of ventral frontal lobe damage (including the orbitofrontal cortex) in humans appear to be related to this type of function, of altering behavior when stimulus-reinforcement associations alter. Thus, humans with ventral frontal lobe damage can show impairments in a number of tasks in which an alteration of behavioral strategy is required in response to a change in environmental reinforcement contingencies (see Rolls 1990, 1996a, 1999a; Damasio 1994). Some of the personality changes that can follow frontal lobe damage may be related to a similar type of dysfunction. For example, the euphoria, irresponsibility, lack of affect, and lack of concern for the present or future that can follow frontal lobe damage may also be related to a dysfunction in assessing correctly and altering behavior appropriately in response to a change in reinforcement contingencies.

Some of the evidence supporting this hypothesis is that when the reinforcement contingencies unexpectedly reversed in a visual discrimination task performed for points, patients with ventral frontal lesions made more errors in the reversal (or in a similar extinction) task, and completed fewer reversals, than control patients with damage elsewhere in the frontal lobes or in other brain regions (Rolls et al 1994a). The impairment correlated highly with the socially inappropriate or disinhibited behavior of the patients, and also with their subjective evaluation of the changes in their emotional state since the brain damage. The patients were not impaired in other types of memory task, such as paired associate learning. Bechara and colleagues also have findings that are consistent with these in patients with frontal lobe damage when they perform a gambling task (Bechara et al 1994, 1996, 1997; see also Damasio 1994). The patients could choose cards from four decks. The patients with frontal damage were more likely to choose cards from a deck which gave rewards with a reasonable probability but also had occasional

very heavy penalties. The net gains from this deck were lower than from the other deck. In this sense, the patients were not affected by the negative consequences of their actions: They did not switch from the deck of cards that though providing significant rewards, also led to large punishments.

To investigate the possible significance of face-related inputs to the orbitofrontal visual neurons described above, the responses of the same patients to faces were also tested. Tests of face (and also voice) expression decoding were included because these are ways in which the reinforcing quality of individuals is often indicated. The identification of facial and vocal emotional expression was found to be impaired in a group of patients with ventral frontal lobe damage who had socially inappropriate behavior (Hornak et al 1996, Rolls 1999c). The expression identification impairments could occur independently of perceptual impairments in facial recognition, voice discrimination, or environmental sound recognition. This provides a further basis for understanding the functions of the orbitofrontal cortex in emotional and social behavior, in that processing of some of the signals normally used in emotional and social behavior is impaired in some of these patients. Imaging studies in humans show that parts of the prefrontal cortex can be activated when mood changes are elicited, but it is not established that some areas are concerned only with positive or only with negative mood (Davidson & Irwin 1999). Indeed, this seems unlikely, in that the neurophysiological studies show that different individual neurons in the macaque orbitofrontal cortex respond to either some rewarding or some punishing stimuli, and that these neurons can be intermingled (Rolls 1999a).

Output Systems

The orbitofrontal cortex and amygdala have connections to output systems such as the striatum through which different types of emotional response can be produced, as illustrated schematically in Figure 2. The outputs of the reward and punishment systems must be treated by the action system as being the goals for action. The action systems must be built to try to maximize the activation of the representations produced by rewarding events and to minimize the activation of the representations produced by punishers or stimuli associated with punishers (Rolls 1999a). Drug addiction produced by psychomotor stimulants such as amphetamine and cocaine can be seen as activating the brain at the stage where the outputs of the amygdala and orbitofrontal cortex, which provide representations of whether stimuli are associated with rewards or punishers, are fed into the ventral striatum and other parts of the basal ganglia as goals for the action system (see Robbins et al 1989, Rolls 1999a, Everitt et al 2000).

Dopamine can be released into this system by aversive as well as by rewarding stimuli (Gray et al 1997). Thus, although Schultz and colleagues (Schultz 1998, Schultz et al 1993, Mirenowicz & Schultz 1996) have argued that dopamine neurons may fire to stimuli that are rewarding or to stimuli that predict reward, such neurons might just respond to the earliest stimulus in a trial that indicates

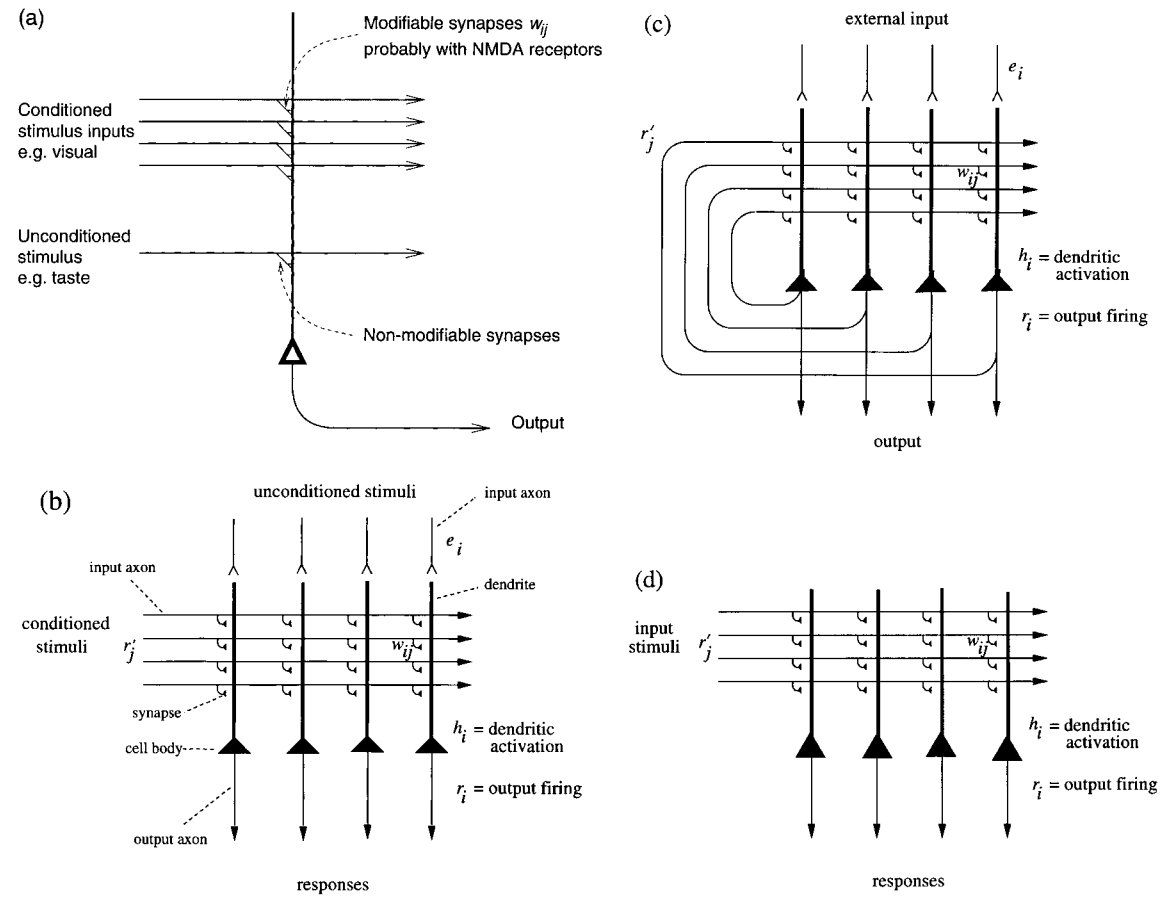


Figure 3 Three neural network architectures that use local learning rules. (a) Pattern association introduced with a single output neuron; (b) pattern association network; (c) autoassociation network; (d) competitive network. (After Rolls & Treves 1998, Figure 1.7)

that an action should be made or that preparation for action should begin (see Rolls 1999a, 2000a; Rolls et al 1983). A crucial test here will be whether dopamine neurons fire in relation to active avoidance of aversive stimuli. It is noted in any case that if the release of dopamine does turn out to be related to reward, then it apparently does not represent all the sensory specificity of a particular reward or goal for action, which instead is represented by neurons in brain regions such as the orbitofrontal cortex (see further Rolls 1999a, 2000a).

Emotion may also facilitate the storage of memories. One way this occurs is that episodic memory (i.e. one's memory of particular episodes) is facilitated by emotional states. This may be advantageous because storing many details of the prevailing situation when a strong reinforcer is delivered may be useful in generating appropriate behavior in similar situations in the future. This function may be implemented by the relatively nonspecific projecting systems to the cerebral cortex and hippocampus, including the cholinergic pathways in the basal forebrain and medial septum, and the ascending noradrenergic pathways (see Rolls 1999a, Rolls & Treves 1998). A second way in which emotion may affect the storage of memories is that the current emotional state may be stored with episodic memories, providing a mechanism for the current emotional state to affect which memories are recalled. A third way that emotion may affect the storage of memories is by guiding the cerebral cortex in the representations of the world that are set up. For example, in the visual system it may be useful for perceptual representations or analyzers to be built that are different from each other if they are associated with different reinforcers, and for these to be less likely to be built if they have no association with reinforcement. Ways in which backprojections from parts of the brain important in emotion (such as the amygdala) to parts of the cerebral cortex could perform this function are discussed by Rolls & Treves (1998).

Neural Networks for Stimulus-Reinforcer Association Learning

The neural networks appropriate for this type of learning are pattern associators, in which the forcing or unconditioned stimulus is the primary reinforcer that must activate the neurons through nonmodifiable synapses, and the to-be-associated stimulus activates the output neurons through Hebb modifiable synapses (Figure 3a,b). Nonlinearity in the neurons (requiring as little as a threshold for firing, a property of all neurons), some heterosynaptic long-term depression as well as long-term potentiation, and sparse representations (i.e. distributed representations with a somewhat low proportion of the neurons active) enable large numbers of memories to be stored in such pattern association neural networks. The number of such pattern pairs p that can be associated is proportional to the number of modifiable synaptic connections C (used for the conditioned stimuli) onto each neuron, and is given by

$$p \gg C/[a_0 \log(1/a_0)],$$

where a_0 is the sparseness of the representation of the output neurons produced by the unconditioned stimulus (for binary neurons the sparseness is simply the proportion of neurons active to any one stimulus) (see Rolls & Treves 1998). For a network with 10,000 connections per neuron, and a sparseness a_0 of 0.02, the number of such pattern associations is in the order of 36,000 (Rolls & Treves 1998).

THE LEARNING OF INVARIANT REPRESENTATIONS

There is strong evidence that some neurons in the inferior temporal cortex and cortex in the superior temporal sulcus have representations of faces and objects that show considerable invariance with respect to changes in position on the retina (shift or translation invariance), size, and even view (Gross 1992; Hasselmo et al 1989b; Rolls 1992, 1997b; Logothetis et al 1995; Booth & Rolls 1998; Rolls & Treves 1998; Wallis & Rolls 1997). There is considerable interest in how these invariant representations might be set up. One hypothesis is that they are set up by a learning process (which must be incorporated in the correct neural architecture). This process involves what is essentially a simple Hebbian associative learning rule, but which includes a short memory trace of preceding neuronal activity (in e.g. the postsynaptic term) (Földiák 1991, Rolls 1992, Wallis & Rolls 1997, Rolls & Treves 1998). The underlying idea is that because real objects viewed normally in the real world have continuous properties in space and time, an object might activate neuronal feature analysers at the next stage of cortical processing, and when the object is transformed (e.g. to a nearby position, size, view, etc) over a short period (for example 0.5 s), the membrane of the postsynaptic neuron would still be in its "Hebb-modifiable" state, and the presynaptic afferents activated with the object in its new transform would thus be strengthened on the still-activated postsynaptic neuron. It is suggested that the short temporal window (0.5 s) of Hebb-modifiability in this system helps neurons learn the statistics of objects moving and thus transforming in the physical world, and at the same time helps them form different representations of different feature combinations or objects, as these are physically discontinuous and present fewer regular correlations to the visual system. (In the real world, objects are normally viewed for periods of a few hundred milliseconds, with perhaps then saccades to another part of the same object, and finally a saccade to another object in the scene.) It is this temporal pattern with which the world is viewed that enables the network to learn using only a Hebb-rule with a short memory trace. The actual mechanism of the trace might be implemented by relatively long-lasting effects of the activation of NMDA receptors, e.g. relatively slow unbinding of glutamate from the NMDA receptor lasting 100 ms or more. Another suggestion is that a memory trace for what has been seen in the last 300 ms appears to be implemented by a mechanism

as simple as continued firing of inferior temporal cortex neurons after the stimulus has disappeared, as has been shown to occur (Rolls & Tovee 1994, Rolls et al 1994b), probably implemented by cortical recurrent collateral associative connections setting up attractor networks (Rolls & Treves 1998).

It is suggested that this process takes place gradually over most stages of the multiple-layer cortical processing hierarchy from V1 (the primary visual cortex) to the inferior temporal cortex (see Figure 1), with each stage receiving inputs from a small part of the preceding stage, so that invariances are learned first over small regions of space, about quite simple feature combinations, and then over successively larger regions. This limits the size of the connection space within which correlations must be sought. It is an important part of this suggestion that combinations of features that bind together in their correct spatial configuration are learned early on in the process, in order to solve the feature binding problem (MCM Elliffe, ET Rolls & M Stringer, in preparation). It is also suggested that each stage operates essentially as a competitive network (see Figure 3d; Rolls & Treves 1998) that can learn such feature combinations, and that the trace rule can then learn invariant representations of such spatially-bound feature combinations (Rolls 1992).

In this functional network architecture, view-independent representations could be formed by the same type of trace-rule learning, operating to combine a limited set of views of objects. Many investigators have proposed the plausibility of providing view-independent recognition of objects by combining a set of different views of objects (Poggio & Edelman 1990, Rolls 1992, Logothetis et al 1995, Ullman 1996). Consistent with the suggestion that the view-independent representations are formed by combining view-dependent representations in the primate visual system, is the fact that in the temporal cortical visual areas, neurons with view-independent representations of faces and objects are present in the same cortical areas as neurons with view-dependent representations (from which the view-independent neurons could receive inputs) (Hasselmo et al 1989b, Perrett et al 1987, Booth & Rolls 1998).

This hypothesis has been tested in a simulation, VisNet, which has a 4-layer architecture that incorporates convergence from a limited area of one stage to the next and feedforward competitive nets trained by a trace rule within each stage. The synaptic learning rule used in VisNet is as follows:

$$dw_{ij} = km_i r'_j \quad (1)$$

and

$$m_i^{(t)} = (1 - \eta)r_i^{(t)} + \eta m_i^{(t-1)}, \quad (2)$$

where r'_j is the j th input to the i th neuron, r_i is the output of the i th neuron, w_{ij} is the j th weight on the i th neuron, η governs the relative influence of the trace and the new input (it takes values in the range 0–1 and is typically 0.4–0.6), and m_i^0 represents the value of the i th cell's memory trace at time t . To train the network to produce a translation invariant representation, one stimulus is placed succes-

sively in a sequence of positions across the input (or “retina”), then the next stimulus is placed successively in the same sequence of positions across the input, and so on through the set of stimuli. To train on view invariance, different views of the same object are shown in succession, then different views of the next object are shown in succession, and so on. The network is able to learn translation and view-invariant representations of objects, provided that it is trained with the trace rule (Wallis & Rolls 1997). In control tests, it is shown not to learn invariant representations when trained with just a Hebbian rule.

There have been a number of recent investigations to further explore this type of learning. In one investigation, Parga & Rolls (1998) incorporated the associations between exemplars of the same object in the recurrent synapses of an autoassociative (attractor) network, so that the techniques of statistical physics could be used to analyze the storage capacity of a system implementing invariant representations in this way. They showed that such networks did have an object phase in which the presentation of any exemplar (e.g. view) of an object would result in the same firing state as other exemplars of the same object, and that the number of different objects that could be stored is proportional to the number of synapses per neuron divided by the number of views of each object. Rolls & Milward (1999) explored the operation of the trace learning rule used in the VisNet architecture further, and showed that the rule operated especially well if the trace incorporated activity from previous presentations of the same object but there was no contribution from the current neuronal activity being produced by the current exemplar of the object. The explanation for this is that this temporally asymmetric rule (the presynaptic term from the current exemplar and the trace from the preceding exemplars) encourages neurons to respond to the current exemplar in the same way as they did to previous exemplars. ET Rolls & SM Stringer (submitted for publication) went on to show that part of the power of this type of trace rule can be related to gradient descent and temporal-difference (see Sutton & Barto 1998) learning.

Consistent with this hypothesis, there is evidence that rapid learning is implemented in the inferior temporal visual cortex. For example, Rolls et al (1989a) showed that neurons rapidly adjusted their responses (in 1–2 s for each stimulus) into a profile of firing to a new set of faces, which enabled the neurons to discriminate between the faces, and Tovee et al (1996) showed that neurons came to respond to ambiguous black and white images that contained faces with just a few seconds of viewing the same pictures in greyscale images in which the faces could be clearly seen. In studies aimed to investigate the neural basis of semantic memory, Miyashita and colleagues (see Miyashita 2000, Higuchi & Miyashita 1996) have shown that inferior temporal cortex neurons can have similar responses to pairs of visual stimuli that regularly occur separated from each other by 1–3 sec, and that the learning of these associations may depend on the perirhinal cortex, which has backprojections to the inferior temporal visual cortex, and which could help to produce maintained firing in response to a stimulus in the inferior temporal visual cortex (Figure 4). The delays involved in these exper-

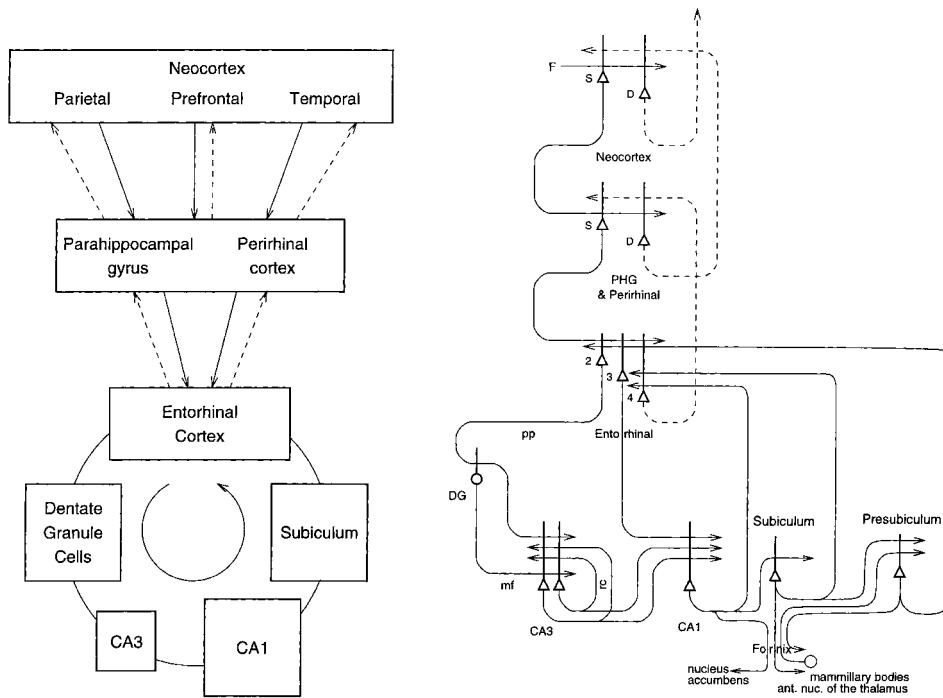


Figure 4 Forward connections (*solid lines*) from areas of cerebral association neocortex via the parahippocampal gyrus and perirhinal cortex, and entorhinal cortex, to the hippocampus; backprojections (*dashed lines*) via the hippocampal CA1 pyramidal cells, subiculum, and parahippocampal gyrus to the neocortex. There is great convergence in the forward connections down to the single network implemented in the CA3 pyramidal cells, and great divergence again in the backprojections. *Left*: block diagram. *Right*: more detailed representation of some of the principal excitatory neurons in the pathways. Abbreviations: D, deep pyramidal cells; DG, dentate granule cells; F, forward inputs to areas of the association cortex from preceding cortical areas in the hierarchy; mf, mossy fibres; PHG, parahippocampal gyrus and perirhinal cortex; pp, perforant path; rc, recurrent collateral of the CA3 hippocampal pyramidal cells; S, superficial pyramidal cells; 2, pyramidal cells in layer 2 of the entorhinal cortex; 3, pyramidal cells in layer 3 of the entorhinal cortex. The *thick lines* above the cell bodies represent the dendrites.

iments are longer than those needed for learning invariant representations of objects (in which the time taken to transform from one view to another might be 100–500 ms), but nevertheless the fact that at least entorhinal cortex neurons can help to bridge delay periods by maintaining firing for a short period after a stimulus has disappeared (Suzuki et al 1997) may be useful in the learning of view-invariant representations. Indeed, Buckley et al (1998) have shown that perirhinal lesions may impair the learning of new view-invariant representations of objects.

THE HIPPOCAMPUS AND MEMORY

Partly because of the evidence that anterograde amnesia occurs in humans with bilateral damage to the hippocampus and nearby parts of the temporal lobe (Squire 1992, Rempel-Clower et al 1996), there is continuing interest in how the hippocampus and connected structures operate in memory. The effects of damage to the hippocampus indicate that the very long-term storage of information is not in the hippocampus, at least in humans. On the other hand, the hippocampus does appear to be necessary to learn certain types of information, which have been characterized as declarative, or knowing that, as contrasted with procedural, or knowing how, which is spared in amnesia. Declarative memory includes what can be declared or brought to mind as a proposition or an image. Declarative memory includes episodic memory (memory for particular episodes) and semantic memory (memory for facts) (Squire 1992, Squire & Knowlton 1995).

Effects of Damage to the Hippocampus and Connected Structures on Memory

In monkeys, damage to the hippocampus or to some of its connections, such as the fornix, produces deficits in learning about where objects are and where responses must be made (Rolls 1996b). For example, macaques and humans with damage to the hippocampus or fornix are impaired in object-place memory tasks in which not only the objects seen, but where they were seen, must be remembered (Gaffan & Saunders 1985, Parkinson et al 1988, Smith & Milner 1981). Such object-place tasks require a whole-scene or snapshot-like memory (Gaffan 1994). Also, fornix lesions impair conditional left-right discrimination learning, in which the visual appearance of an object specifies whether a response is to be made to the left or the right (Rupniak & Gaffan 1987). A comparable deficit is found in humans (Petrides 1985). Fornix-sectioned monkeys are also impaired in learning on the basis of a spatial cue for which object to choose (e.g. if two objects are on the left, choose object A, but if the two objects are on the right, choose object B) (Gaffan & Harrison 1989a). Further, monkeys with fornix damage are also impaired in using information about their place in an environment. For example, Gaffan & Harrison (1989b) found learning impairments when the position of the monkey in the room determined which of two or more objects the monkey had to choose. Rats with hippocampal lesions are impaired in using environmental spatial cues to remember particular places (Jarrard 1993), and it has been argued that the necessity to utilize allocentric spatial cues (Cassaday & Rawlins 1997), to utilize spatial cues or bridge delays (Jackson et al 1998), or to perform relational operations on remembered material (Eichenbaum 1997) may be characteristic of the deficits.

One way of relating the impairment of spatial processing to other aspects of hippocampal function (including the memory of recent events or episodes in humans) is to note that this spatial processing involves a snapshot type of memory,

in which one whole scene with its often unique set of elements must be remembered. This memory may then be a special case of episodic memory, which involves an arbitrary association of a set of spatial and/or nonspatial events that describe a past episode. For example, the deficit in paired-associate learning in humans (Squire 1992) may be especially evident when this involves arbitrary associations between words, for example window and lake.

It appears that the deficits in recognition memory (tested, for example, for visual stimuli seen recently in a delayed match to sample task) produced by damage to this brain region are related to damage to the perirhinal cortex, which receives from high order association cortex and has connections to the hippocampus (Figure 4) (Zola-Morgan et al 1989, 1994; Suzuki & Amaral 1994a,b). Given that some topographic segregation is maintained in the afferents to the hippocampus through the perirhinal and parahippocampal cortices (Amaral & Witter 1989; Suzuki & Amaral 1994a,b), it may be that these areas are able to subservise memory within one of these topographically separated areas; whereas the final convergence afforded by the hippocampus into a single network in CA3 that may operate by autoassociation (see Figure 4 and below) allows arbitrary associations between any of the inputs to the hippocampus, e.g. spatial, visual object, and auditory, which may all be involved in typical episodic memories (see below and Rolls 1996b, Rolls & Treves 1998).

Neurophysiology of the Hippocampus and Connected Areas

In the rat, many hippocampal pyramidal cells fire when the rat is in a particular place, as defined, for example by the visual spatial cues in an environment such as a room (O'Keefe 1990, 1991; Kubie & Muller 1991). There is information from the responses of many such cells about the place where the rat is in the environment. When a rat enters a new environment B connected to a known environment A, there is a period in the order of 10 minutes in which, as the new environment is learned, some of the cells that formerly had place fields in A develop place fields in B instead. It is as if the hippocampus sets up a new spatial representation that can map both A and B, keeping the proportion of cells active at any one time approximately constant (Wilson & McNaughton 1993). Some rat hippocampal neurons are found to be more task-related, responding, for example to olfactory stimuli to which particular behavioral responses must be made (Eichenbaum 1997), and some of these neurons may show place-related responses in different experiments.

It was recently discovered that in the primate hippocampus, many spatial cells have responses not related to the place where the monkey is, but instead related to the place where the monkey is looking (Rolls et al 1997a, Rolls 1999b). These are called spatial view cells. These cells encode information in allocentric (world-related, as contrasted with egocentric) coordinates (Georges-François et al 1999, Rolls et al 1998). They can in some cases respond to remembered spatial views, in that they respond when the view details are obscured, and use idiothetic cues,

including eye position and head direction, to trigger this memory recall operation (Robertson et al 1998). Another idiothetic input that drives some primate hippocampal neurons is linear and axial whole body motion (O'Mara et al 1994), and in addition, the primate presubiculum has been shown to contain head direction cells (Robertson et al 1999).

Part of the interest in spatial view cells is because they could provide the spatial representation required to enable primates to perform object-place memory, for example remembering where they saw a person or object, which is an example of an episodic memory, and indeed similar neurons in the hippocampus respond in object-place memory tasks (Rolls et al 1989b). Associating such a spatial representation with a representation of a person or object could be implemented by an autoassociation network implemented by the recurrent collateral connections of the CA3 hippocampal pyramidal cells (Rolls 1989, 1996b, Rolls & Treves 1998). In the object-place memory task some other primate hippocampal neurons respond to a combination of spatial information and information about the object seen (Rolls et al 1989b). Further evidence for this convergence of spatial and object information in the hippocampus is that in another memory task for which the hippocampus is needed—learning where to make spatial responses when a picture is shown—some primate hippocampal neurons respond to a combination of which picture is shown, and where the response must be made (Miyashita et al 1989, Cahusac et al 1993).

These primate spatial view cells are thus unlike place cells found in the rat (O'Keefe 1979, Muller et al 1991). Primates, with their highly developed visual and eye movement control systems, can explore and remember information about what is present at places in the environment without having to visit those places. Such spatial view cells in primates would thus be useful as part of a memory system, in that they would provide a representation of a part of space that would not depend on exactly where the monkey or human was, and that could be associated with items that might be present in those spatial locations. An example of the utility of such a representation in humans would be remembering where a particular person had been seen. The primate spatial representations would also be useful in remembering trajectories through environments, of use for example in short-range spatial navigation (O'Mara et al 1994, Rolls 1999b).

The representation of space in the rat hippocampus, which is of the place where the rat is, may be related to the fact that with a much less developed visual system than the primate, the rat's representation of space may be defined more by the olfactory and tactile as well as distant visual cues present, and may thus tend to reflect the place where the rat is. An interesting hypothesis on how this difference could arise from essentially the same computational process in rats and monkeys is as follows (see Rolls 1999b). The starting assumption is that in both the rat and the primate, the dentate granule cells and the CA3 and CA1 pyramidal cells respond to combinations of the inputs received. In the case of the primate, a combination of visual features in the environment will over a typical viewing angle of perhaps 10–20 degrees result in the formation of a spatial view cell, the

effective trigger for which will thus be a combination of visual features within a relatively small part of space. In contrast, in the rat, given the extensive visual field that may extend over 180–270 degrees, a combination of visual features formed over such a wide visual angle would effectively define a position in space, that is a place. The actual processes by which the hippocampal formation cells would come to respond to feature combinations could be similar in rats and monkeys, involving, for example competitive learning in the dentate granule cells, autoassociation learning in CA3 pyramidal cells, and competitive learning in CA1 pyramidal cells (Rolls 1989, 1996b; Treves & Rolls 1994; Rolls & Treves 1998). Thus, spatial view cells in primates and place cells in rats might arise by the same computational process but be different by virtue of the fact that primates are foveate and view a small part of the visual field at any one time, whereas the rat has a very wide visual field. Although the representation of space in rats may therefore be in some ways analogous to the representation of space in the primate hippocampus, the difference does have implications for theories, and modeling, of hippocampal function.

In rats, the presence of place cells has led to theories that the rat hippocampus is a spatial cognitive map and can perform spatial computations to implement navigation through spatial environments (O'Keefe & Nadel 1978, O'Keefe 1991, Burgess et al 1994). The details of such navigational theories could not apply in any direct way to what is found in the primate hippocampus. Instead, what is applicable to both the primate and rat hippocampal recordings is that hippocampal neurons contain a representation of space (for the rat, primarily where the rat is, and for the primate, primarily of positions "out there" in space), which is a suitable representation for an episodic memory system. In primates, this would enable one to remember, for example, where an object was seen. In rats, it might enable memories to be formed of where particular objects (for example those defined by olfactory, tactile, and taste inputs) were found. Thus, in primates, and possibly also in rats, the neuronal representation of space in the hippocampus may be appropriate for forming memories of events (which in these animals usually have a spatial component). Such memories would be useful for spatial navigation, for which according to the present hypothesis the hippocampus would implement the memory component but not the spatial computation component. Evidence that what neuronal recordings have shown is represented in the non-human primate hippocampal system may also be present in humans is that regions of the hippocampal formation can be activated when humans look at spatial views (Epstein & Kanwisher 1998, O'Keefe et al 1998).

Hippocampal Models

These neuropsychological and neurophysiological analyses are complemented by neuronal network models of how the hippocampus could operate to store and retrieve large numbers of memories (Rolls 1989, 1996b; Treves & Rolls 1994; Rolls & Treves 1998). One key hypothesis (adopted also by McClelland et al

1995) is that the hippocampal CA3 recurrent collateral connections provide a single autoassociation network that enables the firing of any set of CA3 neurons representing one part of a memory to be associated with the firing of any other set of CA3 neurons representing another part of the same memory (cf Marr 1971). Another key part of the quantitative theory is that not only can retrieval of a memory to an incomplete cue be performed by the operation of the associatively modified CA3 recurrent collateral connections, but also that recall of that information to the neocortex can be performed via CA1 and the hippocampo-cortical and cortico-cortical backprojections (Treves & Rolls 1994, Rolls 1996b, Rolls & Treves 1998). This and other computational approaches to hippocampal function are included in *Hippocampus* 6 (6) (1996).

SHORT TERM MEMORY

A common method the brain uses to implement a short term memory is to maintain the firing of neurons during a short memory period after the end of a stimulus. In the inferior temporal cortex this firing may be maintained for a few hundred ms even when the monkey is not performing a memory task (Rolls & Tovee 1994, Rolls et al 1994b, 1999b; cf Desimone 1996). In more ventral temporal cortical areas such as the entorhinal cortex the firing may be maintained for longer periods in delayed match to sample tasks (Suzuki et al 1997), and in the prefrontal cortex for even tens of seconds (see Fuster 1997). In the dorsolateral and inferior convexity prefrontal cortex the firing of the neurons may be related to the memory of spatial responses or objects (Goldman-Rakic 1996, Wilson et al 1993) or both (Rao et al 1997), and in the principal sulcus/frontal eye field/arcuate sulcus region the neurons may be related to the memory of places for eye movements (Funahashi et al 1989). The firing may be maintained by the operation of associatively modified recurrent collateral connections between nearby pyramidal cells producing attractor states in autoassociative networks (Amit 1995, Rolls & Treves 1998; Figure 3c). For the short term memory to be maintained during periods in which new stimuli are to be perceived, there must be separate networks for the perceptual and short term memory functions, and indeed two coupled networks, one in the inferior temporal visual cortex for perceptual functions, and the other in the prefrontal cortex for maintaining the short term memory during intervening stimuli, provide a precise model of the interaction of perceptual and short term memory systems (Renart et al 1999).

CONCLUSION

It is now possible not only to delineate brain systems involved in different types of memory, but also to have some insight into the neuronal operations that take place in each of these brain systems, and thus to be able to produce quantitative biologically plausible neuronal network models of how each of these memory

systems actually operates, as described more fully by Rolls & Treves (1998). Moreover, this start of a fundamental understanding through a neurocomputational approach of how the brain actually operates quantitatively to implement memory provides the promise of understanding not only how parts of the brain involved in memory operate, but also how many other parts of the brain perform their functions—including sensory information processing to the level of the invariant representation of objects, processing involved in motivation and emotion, and the processing involved in initiating and controlling actions (Rolls & Treves 1998, Rolls 1999a).

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