

Reviews

The functional anatomy of memory

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Abstract. A review of recent work using Positron Emission Tomography (PET) to examine brain systems involved in auditory-verbal memory is presented. Initial work delineated widespread brain regions which were, to a large extent, in agreement with existing neuropsychological literature. Expanding on this, a number of studies have examined memory encoding and retrieval separately. Additionally, experiments have been carried out to specifically address sub-components of memory such as the use of visual imagery as a mnemonic strategy, the functional anatomical evidence for the episodic/semantic memory distinction and the different brain regions involved in explicit and implicit memory tasks.

Key words. PET; memory; encoding; retrieval.

Defining memory

"I have done that," says my memory. "I cannot have done that" says my pride. . . . At last-memory yields."

Friederich Nietzsche

The vast and multi-faceted nature of memory frequently defies description let alone definition. Etymologically, its root lies in *memor* – 'mindful' and *memorare* – 'a bringing to mind'. However, the experience of conscious recollection, which is perhaps a sine qua non of the everyday concept of memory, fails to address the fact that there are memories which govern and qualify behaviour yet are never consciously recollected. For example, to use a word correctly is to remember its meaning and its syntactic properties. To drive a nail is to remember a complex sequence of muscle movements which bring the hammer squarely onto its head. Yet it feels unnatural to group either of these 'memories' with the vivid recollection of past events which constitutes the everyday concept. If one looks up a telephone number, in the interval between finding it, reading it and dialling it, it is held in memory. This 'holding' may require an inner rehearsal of the number such that, if there is an interruption, it may have to be looked up again. Subsequently it may disappear without trace, being irretrievable by even the most thorough of mental searches. The memory of the ensuing telephone call, however, will more than likely remain. Its outline can be recalled fairly accurately hours, days, weeks or (if the conversation was of sufficient import) even years afterwards. If the same number is dialled frequently enough it may become so embedded in memory that there may be no recall of ever

having to look it up. It may even be dialled automatically without explicitly recalling the numbers, and, in some cases, by mistake, when the intention was to dial another number. All of these, the process which allows us to carry a telephone number from phone book to phone, the rich recollection of a complex conversation, the ingraining of a sequence of digits so that it can be repeated or dialled almost automatically, together with the knowledge of what a telephone is and how to use it, all come under the rubric of memory.

Added to these, there are further complexities. What of memories in other sensory modalities? What of memories which we are sure of possessing yet cannot access (the 'tip-of-the-tongue' phenomenon)? What of the current interest in memories that we never knew we possessed and yet seem to access ('false memory/recovered memory')? What of the palimpsestic nature of some of our memories – the unconscious and sometimes profound warping to which Nietzsche refers above?

Amid the welter of qualification and apparent paradox, a definition is of little use. Memory is not a unitary phenomenon and its study has been best served by a taxonomy which isolates sub-components and informs hypotheses about the characteristics of these sub-components, together with their relationship to other sub-components in the system. In the following review, we shall refer to such a taxonomy²⁵ and outline some of the neuropsychological and experimental evidence for its validity. The main aim is to show how Positron Emission Tomography (PET) allows the brain regions involved in normal memory to be described. The results of initial, broad-based experiments, encompassing several facets and sub-divisions of memory, have been refined to provide evidence in support of a taxonomic distinction.

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Further, this approach has enabled the elucidation of separate brain regions which mediate sub-processes of memory tasks. In this treatment, we hope to show the strengths of the techniques which serve as an optimistic indication that complex functions can be examined in terms of functional localisations in the brain.

A structure for memory

Memory is most simply sub-divided into *short-term* and *long-term components*. The former refers to a limited capacity store holding approximately 7 chunks of information for a period of seconds or minutes. This is maintained by rehearsal and is rapidly superseded when attention is switched. Short-term memory is the memory used in maintaining the telephone number during the interval between reading it and dialling it². A number of experimental features of auditory-verbal (as opposed to visual) short-term memory suggest that it is structured as an articulatory/phonological loop in which a short-term phonological store is refreshed by internal rehearsal. In contrast, long-term memory is a system of almost unlimited capacity, holding information for anything up to a lifetime. It may be broadly divided into those memories which are accessible to consciousness (*explicit* or *declarative* memory) and those which are inaccessible to consciousness (*implicit* or *procedural* memory) and, within these, further subdivisions exist (see fig. 1).

Evidence for the taxonomy

Short-term versus long-term memory

This distinction has been a subject of psychological study since the 1950s and an array of evidence has supported it: differences in input and retrieval rate, storage capacity and acoustic/semantic properties, with short-term memory being more rapidly encoded and retrieved, far less capacious and subject to acoustic rather than semantic interference (see ref. 2 for review). Additionally, and perhaps most compellingly, the neuropsychological literature indicates that some patients

suffer an impairment of long-term memory in the presence of intact short-term memory¹⁵ while others have impaired short-term memory with intact long-term memory^{24,31}. This double dissociation provides evidence that the distinction between long- and short-term memories holds good at a neuroanatomical level.

Implicit versus explicit memory

At a descriptive level, the distinction between explicit memories and implicit memories (skills/conditioned responses/priming effects) seems fairly clear-cut. The former are *declarative* – they can be declared or brought to consciousness. The latter are *procedural* – they manifest in cognitive operations and behavioural procedures and, as such, are not the objects of conscious recollection. Stated more simply, declarative memories are *knowing that*, implicit memories are *knowing how*¹⁴. That these forms of memory have different neural representations is evident from studies of patients with profound deficits in explicit memory. Such patients have been repeatedly found to show intact features of implicit memory including priming⁹, skill learning¹⁵ and conditioning³².

Episodic versus semantic memory

This distinction was first described by Endel Tulving although, as he pointed out, his distinction had some precedence in the descriptions of Claparède and Furlong²⁷. Episodic memory refers to memory for episodes. It has an autobiographical context. Semantic memory refers to the knowledge used in the comprehension, organisation and use of symbols (visual as well as verbal). A memory of, for example, Paris could be episodic in which case it would involve the recollection of a specific episode in which Paris was involved. A semantic memory of the same city would comprise the knowledge that it is the capital of France, that it was built around the River Seine, i.e. knowledge which does not require reference to personal experience in the way that an episodic memory does. This descriptive distinction is also backed up by evidence from psychophysical studies²⁷. There is less evidence from neuropsychological literature. A supportive double dissociation, with some patients showing a selective impairment in semantic memory¹⁴ and others a specific episodic memory deficit^{5,27}, has been suggested. However, the distinction is far from clear-cut. Below is described a PET study which has proved some functional anatomical support for the distinction.

The taxonomic distinctions outlined are conceptually useful as a framework for experimental and neuropsychological approaches to memory and their validity has been at least partially buttressed by experimental findings. What has not been addressed is the extent to which such divisions are reflected in the functional anatomy of the brain. Functional imaging is a technique particularly suited to addressing these questions and the use of Positron Emission Tomography (PET) will be

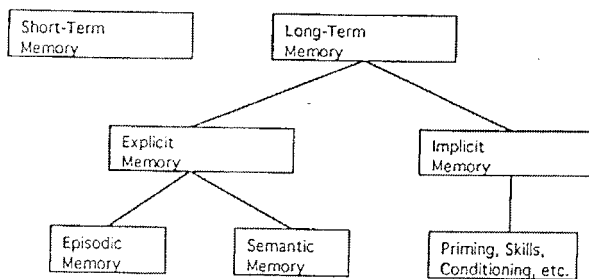


Figure 1. A taxonomy of memory²⁵. Sub-divisions of memory are defined in the text, apart from 'Priming' which refers to an implicit memory which is manifest as a facilitation of a response due to previous exposure to an item which can occur in the absence of explicit memory of that item.

described in the next section with a review of its impact on the study of memory.

Positron Emission Tomography (PET)

PET provides a precise, in vivo, 3-dimensional map of brain activity. The studies described use the positron emitter O (ref. 15) (as either H_2^{15}O given intravenously or C^{15}O_2 inhaled). Positrons, in tissue, collide with electrons. This leads to an annihilation, with the emission of two bursts of gamma radiation (at 180° to each other) which can be measured using a gamma camera. The average regional cerebral distribution of the sources of positron emission over approximately a ninety-second period provide an estimate of cerebral synaptic activity. Each subject can undergo up to 18 such measurements over about a three-hour period. During each measurement, a subject may perform an activation task or an appropriate control task (in the experiments described below, all the activation tasks involve memory. Control tasks are designed to allow the subtraction of confounding features such as vision, speech, hearing, movement, etc., which are inherent in the activation task). The end result is a picture of brain activity associated with performance of the task in question. PET activation tasks are designed with several features in mind:

1) In order to obtain interpretable scans, the subject's head should be kept as still as possible. As well as the use of careful positioning together with helmets, padding, etc., to facilitate this, the task should be designed so that any necessary movements (e.g. during a motor learning paradigm) should be minimised as far as possible and confined to the extremities. In addition, the subject's constrained field of view means that visually presented study material should be optimally displayed (although the advent of new scanner designs may overcome this latter problem).

2) Brain activity is measured over approximately ninety seconds. The subject must be performing the task for at least thirty seconds of this period (the phase when the ^{15}O is being taken up into the brain). Thus, in order to get a true picture of average brain activity associated with a given task, that task must be performed continually or repeatedly for at least this period (in fact, recent results from this unit seem to suggest that significant alterations in measurable brain activity may be associated with remarkably few events during the scanning period. However, it is generally held that the activation task should be continuous or regularly repeated during the vital thirty seconds).

3) Great care must be taken to design control tasks in order to allow as clear as possible a delineation of the regional cerebral blood flow (rCBF) associated with the cognitive process under study. Since, ultimately, rCBF in the control tasks will be subtracted on a pixel by pixel basis from that in the activation task, using a technique

called Statistical Parametric Mapping (SPM; see ref. 8 for summary) it is vital that the stimulation during both tasks is matched in terms of rate, modality and nature of presentation, total amount of material presented, number of responses required and, where appropriate, attentional demands. In brief, the control task for a memory study should be identical to the activation task except that it does not require the use of memory.

A more recent methodological development, in which experimenters have dispensed with specific control tasks and, instead, systematically manipulated a single variable across the range of scans, has also been applied to memory. This graded task approach will be described below.

Having described the PET technique and its constraints, the next section will examine how, in practice, it can be used to examine memory in the normal brain. The earlier experiments in memory function were designed to examine short-term¹⁷ or long-term memory^{10, 11, 19} (or both) as a whole. Recent work has sought to specifically address separate processes occurring subordinate to the long-term/short-term dichotomy. These include the distinction between brain areas engaged by encoding and retrieval of long-term memory^{7, 13, 22, 26, 29}, the functional anatomical evidence for the episodic/semantic distinction^{7, 22} and, more recently, the effect of varying certain parameters of study material, such as the degree of associated imagery. This progression from the gross and general through to the more refined and specific is described in the section which follows. As well as providing an overview of PET studies in memory, the approach outlined is paradigmatic of the way in which this technique can be applied to generate and test hypotheses which are more specific and informed.

PET studies of short-term memory

A cognitive model of working/short-term memory assigns it a 'central executive' supplemented by two or more slave systems – the 'phonological loop' (specific for language-related memory) and the 'visuo-spatial sketch pad' (for visual material)². The phonological loop has two theoretical components, a sub-vocal rehearsal system and a short-term phonological store. Paulesu and colleagues used a series of tasks designed to elucidate brain systems involved in verbal short-term memory as a whole and to extricate the two components of the phonological loop¹⁷. Healthy subjects were scanned while performing a series of tasks:

1) Lists of letters were presented visually and serially. After completion of each list, there was a brief gap followed by a probe letter. The subject's task was to indicate whether or not the probe had been contained within the list which preceded it. In order to perform this successfully, it was predicted that there would be engagement of verbal short-term memory as a whole,

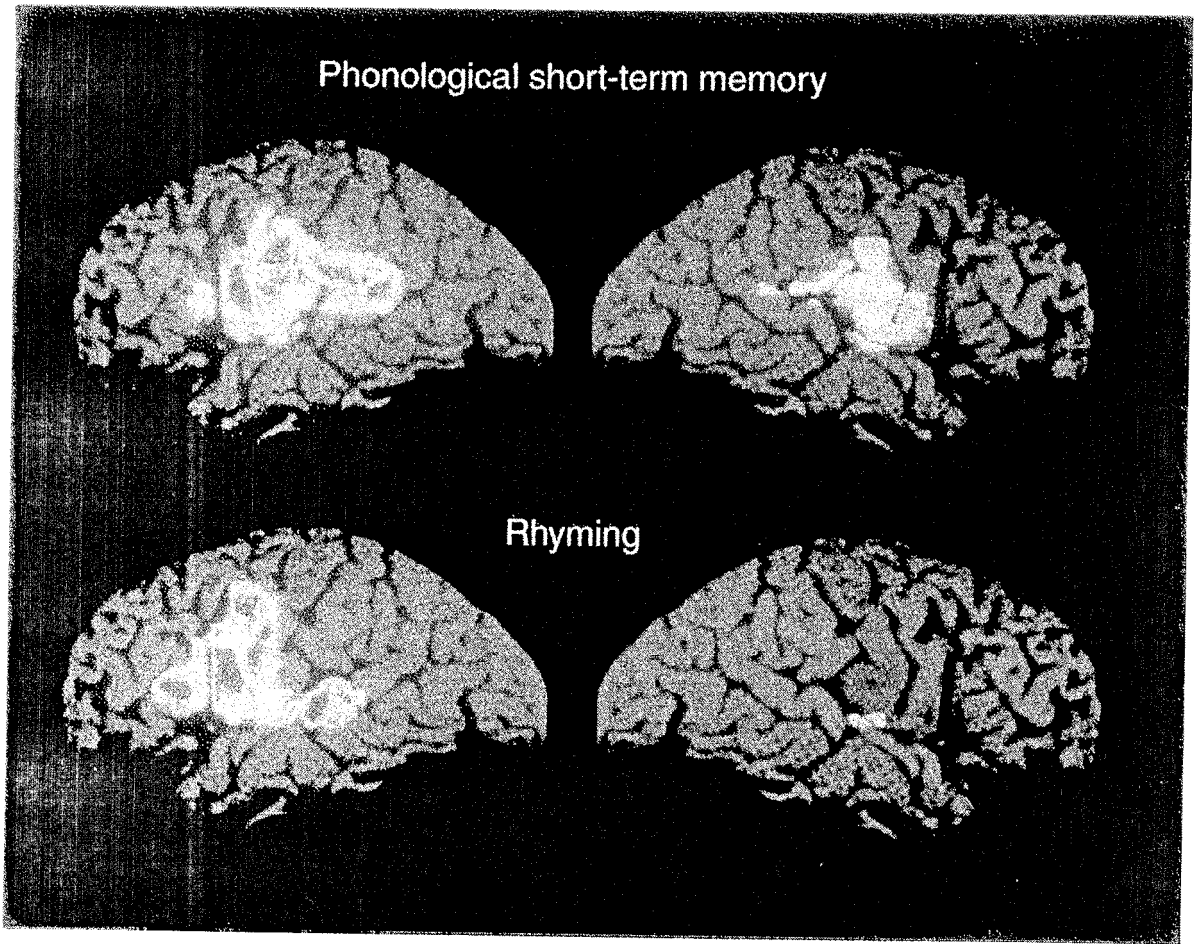


Figure 2. Statistical parametric maps showing brain regions activated in response to short term memory tasks and rhyming tasks in comparison to control tasks (visual memory and shape similarity tasks respectively). Areas of significant activation ($p < 0.001$) are shown superimposed on representative cortical surfaces to give an indication of the anatomy.

(Courtesy of Dr. E. Paulesu)

i.e. both the sub-vocal rehearsal system and the phonological store in unison.

2) A rhyming judgement task. This was felt to exclusively involve sub-vocalisation but not the phonological store.

Both of these tasks were compared directly with tasks with comparable visual input not thought to engage verbal working memory. The first comparison of the short-term memory task with its control showed activation of, among other areas, two main language-associated regions, Broca's area and Wernicke's area, together with a region known as the supra-marginal gyrus. The rhyming task elicited activation of the same areas but not of the supra-marginal gyrus. These results are summarised in fig. 2. The authors concluded that this latter area functions in the role of a phonological store with regions activated by both tasks, subserving sub-vocal rehearsal. This is consistent with lesion studies²³.

PET studies of long-term memory

Explicit/declarative memory

One of the first experiments to address the question of brain regions engaged during an episodic memory task used the immediate free recall of word lists as the memory paradigm¹⁹. In both the activation and the control tasks, subjects were repeatedly presented with lists of words during the scanning period. The activation task comprised word lists consisting of 15 items, i.e. beyond the capacity of short-term memory and necessitating the engagement of long-term memory processes. However such recall would also engage short-term memory since subjects would tend to hold a few of the items in this way. In order to overcome this and to isolate, as purely as possible only those brain regions engaged in long-term memory, the control task required the immediate free recall of 5 item word lists which

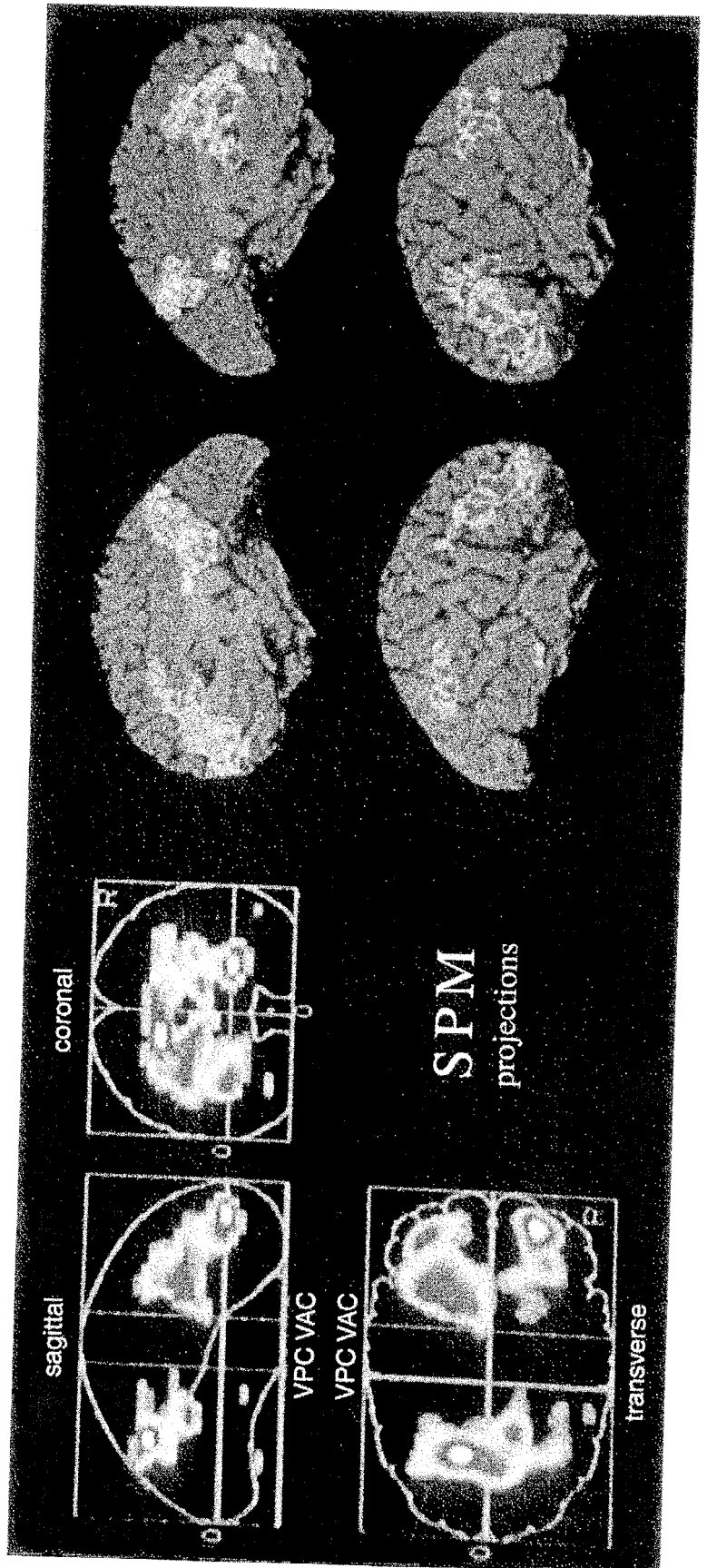


Figure 3. Statistical parametric map of brain areas activated by a long-term memory task (remembering a 15 item word list) compared to a short-term memory task (5 item word list). The images on the left show orthogonal views of brain space seen from the right (sagittal), above (transverse) and behind (coronal). Areas of significant activity ($p < 0.001$) can be localised by examining all three views. On the right, activations are rendered onto representative cortical surfaces as for figure 2. (Courtesy of Dr. P. M. Grasby)

could easily be repeated without recourse to the engagement of long-term memory. Using SPM, subtracting all scans obtained during the 5 item recall from those obtained during the 15 item recall, significant activation of 4 brain areas in association with long-term memory function was found: the left and right prefrontal regions, the precuneus and posterior cingulate cortex (see fig. 3). When the scans from both the 15 item and 5 item word lists were compared with scans obtained while subjects were at rest, there was noted to be additional activation of the thalamus, the anterior cingulate cortex and lateral temporal cortex.

The findings of frontal and posterior cingulate activity is in keeping with existing neuropsychological and experimental data from animals and humans which has identified their importance in memory function^{12,18,21,30}. In other studies using PET the frontal lobes have also been strongly activated in association with tasks involving long-term memory^{11,19}. In the latter study a different technique was employed in which, instead of using two tasks, a memory task and a control task designed to subtract out confounding factors such as auditory-verbal processes, all scans involved the subjects in hearing and repeating word lists, with the amount of load placed on memory being varied from one scan to another (in fact, word lists varied between 2 and 13 items inclusive). Data were then analysed by examining increases in activity associated with increasing word list length. This graded task approach showed activation of similar areas to those seen in the cognitive subtraction study described above. In the other study¹⁹, cognitive subtraction was used, but subjects were required to remember digits rather than words. Despite the difference in study material, similar areas were also activated in this study.

So the earlier exploratory PET studies of the functional anatomy of long-term memory have been strikingly consistent despite using a variety of study material and design. As well as implicating a number of areas which might have been predicted on the basis of previous work, notably the frontal lobes, the thalamus and the posterior cingulate cortex, there have been other findings which, although not obviously predictable, have also proved reliable across different tasks. One notable example is the activation of the precuneus. In the next section, we shall describe how more refined experimental paradigms have allowed examination of the brain regions specific to memory sub-processes (encoding and retrieval), different types of memory (explicit versus implicit), and specific mnemonic strategies (visual imagery).

Separation of brain systems involved in the encoding and retrieval of episodic memory

Encoding

Since some degree of memory encoding is an almost ubiquitous accompaniment of any conscious experience, whether or not a subject makes an effort to 'memorise'

the experience¹⁶, then it follows that, unless control tasks are carefully designed, they will be accompanied by a degree of episodic memory encoding, rendering their comparison with the memory activation task prone to type II error (i.e. false negatives: the failure to find an activation because encoding is occurring in both tasks). Two PET studies have sought to address this problem. One¹³ used a semantic decision with a letter identification task as the control. This design utilises 'levels of processing' theory⁶ which describes the depth of memory encoding in terms of the type of processing which occurs. Thus an item which the subject is required to process semantically will be more 'deeply' encoded (and, subsequently, more efficiently recalled) than one which does not require semantic processing. In this study, it was predicted that the subtraction of scans obtained during the shallow encoding task from those obtained during the deep encoding task would reveal the neural correlates of episodic memory encoding. The comparison between the two tasks showed a significant activation of the left frontal lobe.

The second study^{7,22} used a dual task interference paradigm in which subjects were listened to, and attempted to memorise, lists of category exemplar pairs (e.g. 'fruit . . . lime; vehicle . . . scooter; animal . . . goat; etc'). They did this under two conditions. In the first, memory encoding was accompanied by performance of a distracting task (using a joystick to move a cursor into boxes which appeared rapidly, and in random positions, on a screen). In the second, encoding was accompanied by a non-distracting task (moving the cursor into boxes appearing in a predictable order). This design is based on experimental evidence that the distracting task interferes specifically with episodic memory encoding³ (but not other aspects of the task such as semantic processing and priming) whereas the non-distracting task does not (as was demonstrated by differential performance on cued recall which was tested after each scan). Auditory components of these tasks were subtracted out by employing a control ('passive listening') task in which subjects listened to identically paced pairs which were they could not commit to memory (the words 'one thousand . . . two thousand' repeated throughout the scanning period). The theory behind this approach is simplistically summarised in figure 4.

Despite its markedly different design to the level of processing approach described above, this experiment also indicated activation of the left frontal lobe in association with episodic encoding (in addition, there was noted to be posterior cingulate cortex activation) – see figure 5.

Retrieval

At the time of writing, three PET studies have examined verbal memory retrieval specifically. Each study used a substantially different approach. In the first, a word stem

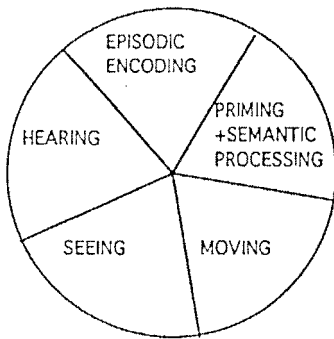
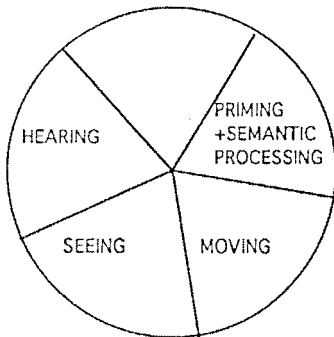
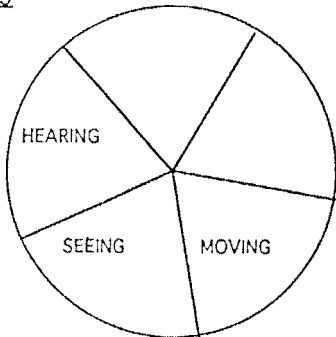
Task 1Task 2Task 3

Figure 4. Diagrammatic representations of tasks used in PET study of episodic memory encoding.

Task 1 – Episodic memory encoding task (paired associate learning) in the presence of the non-distracting motor task.

Task 2 – Paired associate learning in the presence of the distracting task.

Task 3 – Passive listening task.

A comparison of PET scans obtained during task 1 with those during task 2 (subtracting out the auditory and other components by means of task 3) will indicate those brain regions involved in episodic memory encoding (see figure 5).

completion task was employed²⁶, subjects having been presented with a list of 15 study words a few minutes prior to scanning. During the scan, subjects were presented with the first three letters of each word and required to complete these stems to form the previously seen words. When this episodic retrieval condition was compared to control conditions (a baseline condition in which previously unseen word stems were presented, a 'no response' condition and a priming condition [see below]), activation of the right frontal lobe (and, to a

lesser extent, the left), the right hippocampus and a medial parietal region were noted. A further study employing sentence recognition as the paradigm for episodic retrieval²⁹, also showed a predominantly right frontal and medial parietal pattern of activation. In the third study, the cued retrieval of paired associates was examined^{7,22}. Here, identical study material was used to that described in the paired associate encoding experiment but subjects were presented with the material 5 minutes prior to scanning, which took place when they were prompted with the categories and required to respond with the exemplars which they had previously been given (e.g. prompt 'fruit'... response 'lime'; prompt 'vehicle'... response 'scooter'; prompt 'animal'... response 'goat'; etc). Since this task also incorporates retrieval from semantic memory, a control task was employed in which, during scanning, subjects were presented with new categories and required to respond with an exemplar of their own choice. This latter task necessitated retrieval from semantic memory but did not have the episodic memory component (i.e. recalling a specific exemplar given at a specific time). Here again, there was activation of the right frontal lobe and the medial parietal cortex in association with the episodic memory retrieval task (see fig. 5).

Gratifyingly, therefore, despite the use of markedly differing tasks and conditions, PET studies of the separate processes of episodic memory encoding and retrieval have produced remarkably consistent results, with left frontal activation predominating at encoding and right frontal activation at retrieval. The biological significance of this phenomenon has been commented on²⁸ but remains to be explored in depth.

Another consistent finding is the almost ubiquitous activation of the medial parietal region, the precuneus, in PET studies of memory, and, more lately, the finding that this activation is specific to retrieval. In the section which follows, we describe a study which sought to elucidate the function of this largely unexplored area.

The precuneus in memory-related visual imagery

"... they ... form in the mind's eye an image ... and this is recollection"

Plato (*Phaedo*)

Visual imagery is a frequent accompaniment of a variety of cognitive processes and provides a valuable strategy for efficient episodic memory retrieval. In the early PET studies of episodic memory described above^{10,11}, subjects commented upon the use of imagery which many of them had employed in attempting to retrieve study items, and Grasby et al. speculated that this may be reflected in the activations of the precuneus seen strongly in both of these experiments. In the follow-up study, of brain systems involved specifically at retrieval^{7,22}, subjects once again commented upon the

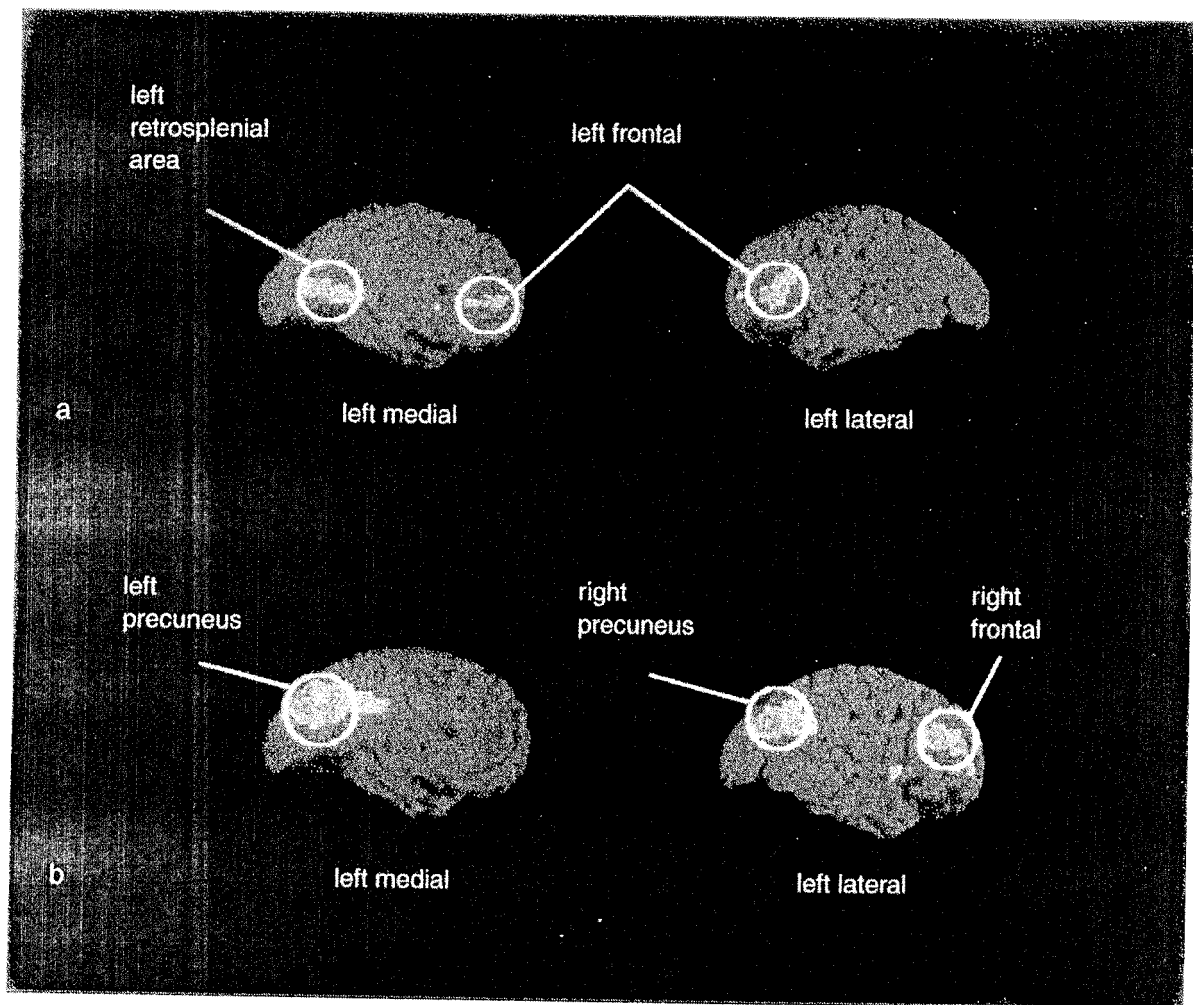


Figure 5. Brain regions activated during encoding (a) and retrieval (b) of episodic memory.

helpfulness of using visual imagery as a mnemonic strategy and, as with the other studies of retrieval^{26,29}, precuneus activation was prominent. Although there is little in the way of neuropsychological evidence about the functional anatomy of the precuneus, these findings led to the design of an experiment to explicitly test the hypothesis that visual imagery in memory retrieval is subserved by this area. Once again we used cued retrieval of verbal paired associates as the paradigm for episodic retrieval. As before, lists of word pairs were presented 5 minutes prior to scanning. Subsequently, during the scan, the first member of each pair was used as the cue to retrieval of the second. Two sets of lists were used. In the first pairs were designated as 'imageable'²⁹ (e.g. 'king...queen; car...truck; train...whistle; etc'). In the second, pairs were designated non-imageable (e.g. 'justice...law; command...order; close...near; etc'). Retrieval of both sets of pairs would, we predicted, engage overlapping memory systems, but a comparison between the two would isolate those specific to the use of visual imagery in memory

retrieval. We ascertained that there was, indeed, a significantly greater degree of imagery associated with recall of the former set by introducing subjective ratings of the frequency and consistency of imagery after each scan. Our prediction, that the precuneus would be significantly more activated by the recall of the imageable pairs was borne out (see fig. 6), thus lending strong support to this hypothesis about its function.

A division within explicit memory – the episodic/semantic distinction

"Probably the most basic issue on which we find disagreement today concerns the problem of whether episodic and semantic memories represent different functional systems... if neuroanatomical and neurophysiological correlates of episodic and semantic memory systems could be identified, the issue of the functional difference between the systems would become redundant"

Tulving²⁷

In the memory retrieval experiment described above^{7,22}, it was possible to examine directly the brain systems involved in both retrieval from episodic memory and

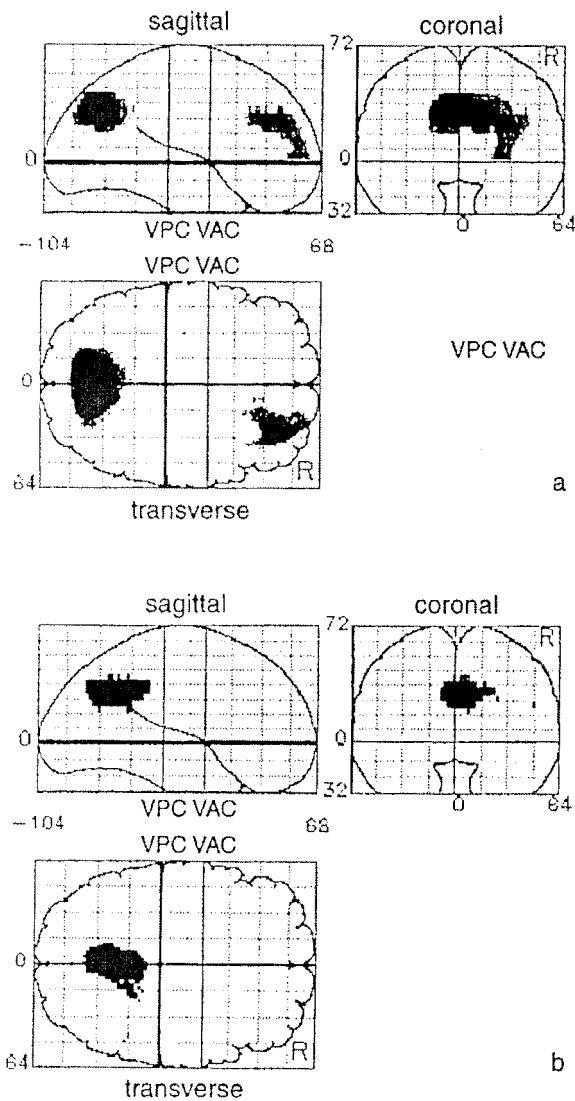


Figure 6. *a*) Brain regions activated by episodic retrieval of paired associate words – the right prefrontal cortex and precuneus are seen.

b) Regions within episodic retrieval system where imageability of the paired associates affect activity. The precuneus is seen to be active in association with retrieval of highly imageable pairs.

from semantic memory by comparing them both, separately, with a control (word repetition) task. This control task in which words were presented at the same pace as those in the two memory tasks enabled the subtraction of the auditory-verbal demands. This subtraction isolated overlapping brain systems in which thalamic and the anterior cingulate cortex activation were noted to be a common to both episodic and semantic retrieval. In addition, the episodic task elicited right frontal and precuneus activation (see fig. 7). As mentioned above, the direct comparison between the tasks (i.e. episodic versus semantic retrieval) showed a

statistically significant difference between the two conditions thus providing functional anatomical support for this taxonomic distinction.

The use of PET to distinguish between explicit and implicit memory

To reiterate the distinction between explicit and implicit memory tasks, the former refers to those which necessitate conscious recollection, the latter to those which demonstrate learning by a change in behaviour without the accompanying consciousness of that learning-knowledge. In an ingenious series of experiments examining memory retrieval, Buckner et al. have explored this taxonomic distinction in functional anatomical terms by manipulating word completion tasks in order to preferentially tax one or other of these forms of memory^{4,6}. Three main activation tasks were used: – 1) Explicit retrieval – Here, subjects were presented with a series of words a few minutes before scanning. Subsequently, they were presented with 3-letter word stems and required to complete these in order to form words which they had previously seen during the study phase. For example, if the word 'GARNISH' had been one of the studied words, then, at some point during the scan, the subjects would be presented with the word stem GAR and required to complete it appropriately. Obviously, to perform this task requires explicit recall of seeing the word previously.

2) Implicit retrieval (priming) – Again subjects were presented with a series of words prior to scanning, and again, during the scan, they were presented with 3-letter stems which they were required to complete. This time, however, their instructions were to complete the stems with the first words that came to mind. This task was predominantly implicit and required no intentional or conscious recall of studied words (even though there was a tendency for subjects to produce those words in response to the appropriate stems).

3) Baseline condition – Subjects were presented, during scanning, with stems which could not be used to form previously seen words. They were instructed to complete the stems with the first word that came to mind. This task did not require explicit recall nor did it involve any implicit component.

Amid several interesting results, a main finding from this study was of right frontal activation in association with the explicit recall condition when compared to the baseline task. This was not found in the priming versus baseline comparison which, in fact, showed no increase in brain activity in association with the implicit retrieval condition. This condition was, however, associated with a decrease in activity located predominantly in the right temporo-occipital region. The authors very plausibly interpreted this in terms of priming being a facilitation of information processing and thus requiring a lesser

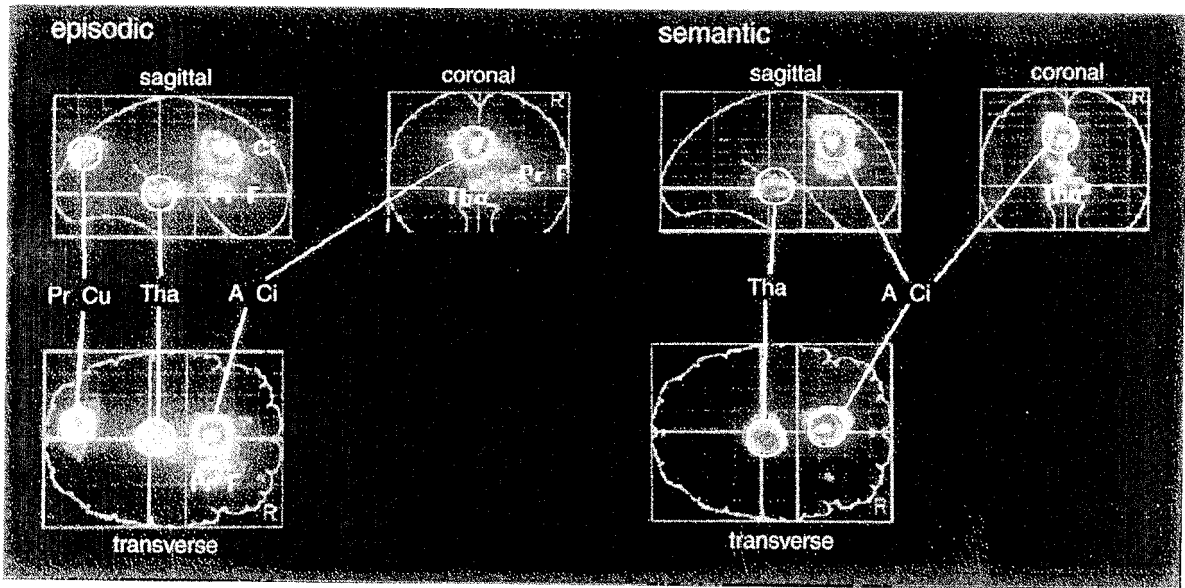


Figure 7. Brain regions activated by episodic and semantic memory retrieval. Common to both tasks is activation of the thalamus (Tha) and the anterior cingulate cortex (A Ci). Unique to the episodic retrieval task is right prefrontal (Pr F) and precuneus (Pr C) activation.

degree of activity to produce responses to the word stems than that required by the baseline task (the suggestion that subjects found the implicit retrieval task easier is lent credence by a measured reduction in reaction times in this task).

Of course PET has limited spatial and, more seriously, temporal resolution. Perhaps these limitations account for one of the more surprising findings associated with PET memory experiments, i.e. the consistent failure to show activation of medial temporal regions. Neuropsychology has produced undeniable evidence for the importance of these regions in memory function. It seems likely that the absence of activation in PET studies reflects a continual activity in these regions such that a cognitive subtraction technique would show no relative increase in activity during the memory task.

In conclusion, the use of PET in the functional imaging of auditory-verbal memory has generated a number of results in support of the existing taxonomy. Additionally, it has provided further evidence for the importance of several brain regions in memory tasks, particularly the frontal lobes, the thalamus and the cingulate cortex. However, the main influence of PET has been in its ability to examine specific sub-components of memory. For example, the differential activation of the right and left prefrontal cortices in episodic memory encoding and retrieval respectively. Such specificity has also enabled an hypothesis-led exploration of the precuneus activation associated with episodic memory retrieval. This medial parietal area has been a puzzling but almost ubiquitous finding in association with PET memory studies. The speculation about its involvement in visual

imagery, and the subsequent confirmation of this through a specifically designed study, is an example of the added dimensions which PET can bring to the study of memory. The limitations in spatial and temporal resolution may be, to a large extent, overcome by the advent of functional magnetic resonance imaging (which is accurate to within several millimetres) and by the application of functional imaging in conjunction with other techniques such as electrophysiological measurements (in which measurements can be made over milliseconds).

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