Components of episodic memory:
the contribution of recollection and familiarity

Andrew P. Yonelinas

Department of Psychology, University of California, Davis, CA 95616 USA (apyonelinas@ucdavis.edu)

The examination of recognition memory confidence judgements indicates that there are two separate components or processes underlying episodic memory. A model that accounts for these results is described in which a recollection process and a familiarity process are assumed to contribute to recognition memory performance. Recollection is assumed to reflect a threshold process whereby qualitative information about the study event is retrieved, whereas familiarity reflects a classical signal-detection process whereby items exceeding a familiarity response criterion are accepted as having been studied. Evidence from cognitive, neuropsychological and neuroimaging studies indicate that the model is in agreement with the existing recognition results, and indicate that recollection and familiarity are behaviourally, neurally and phenomenologically distinct memory retrieval processes.

Keywords: recognition; familiarity; memory; episodic; recollection; explicit

1. INTRODUCTION

The notion that episodic memory consists of distinct components dates back at least to Aristotle. In the 1970s and early 1980s, cognitive psychologists formalized this notion and developed dual-process models that assumed that there were two separate processes, recollection and familiarity, that contributed to episodic recognition memory (e.g. Atkinson & Juola 1974; Jacoby & Dallas 1981; Mandler 1980; Tulving 1985). The idea was that previously studied items would be more familiar than new items, thus subjects could accept the more familiar items as having been studied. However, in addition to assessments of familiarity, if subjects could retrieve some aspect of the study event, such as when or where it occurred, this could also be used as a basis for recognition judgements.

Despite the introspective appeal of the dual-process models and their initial success in accounting for a variety of behavioural results, the dominant theories of that period assumed that recognition memory reflected only a single familiarity process, and recollection was not thought to play a significant, if any, role in recognition memory judgements. In these single process models, recognition was generally assumed to be well described by signal-detection theory (see figure 1). The basic idea is that studied items are on average more familiar than new items, but because the old and new item familiarity distributions overlap it is necessary to set a response criterion and accept only the items above that level of familiarity as having been studied. The advantage of the model is that it uses only a single memory component, thus recognition memory accuracy can be characterized using a single parameter (i.e. d', which is the distance between the old and new item distributions). Over the past 20 years, single process models have become more sophisticated and have included additional assumptions about

how items are represented and how these items are stored in the memory. These include global memory models such as episodic or instance models (e.g. MINERVA, Hintzman 1986), as well as connectionist or distributed models (e.g. TODAM, Murdock 1982). Although the specific assumptions of these models differ, they all maintain that recognition memory judgements rely on the assessment of a single familiarity measure.

Over the past 10 years, however, the limitations of the single process models have become increasingly obvious (see, for example, Clark & Gronlund 1996; Hockley 1991; Ratcliff *et al.* 1992; Yonelinas 1994), and there has been a renewed interest in dual-process theories of recognition memory. The aim of the current paper is to review some of the recognition memory work that my colleagues and I have conducted over the past 10 years. I will first describe a set of findings that demonstrate that there are at least two distinct components of episodic recognition memory. I will argue that these two components reflect the operation of two distinct retrieval processes: recollection and familiarity. I will then describe a dual-process model that was designed to account for these results and review the empirical studies that have been conducted to test the underlying assumptions of that model. I will conclude by discussing the limitations of that model and raise questions for future studies of episodic memory.

2. RECOGNITION RECEIVER OPERATING CHARACTERISTICS

One area of research that turns out to be particularly problematic for the current single process models of episodic memory is the study of receiver operating characteristics (ROCs). A ROC is the function that relates the proportion of correct recognitions (i.e. the hit rate) to the proportion of incorrect recognitions (i.e. the false alarm rate). Typically, performance is examined across levels of
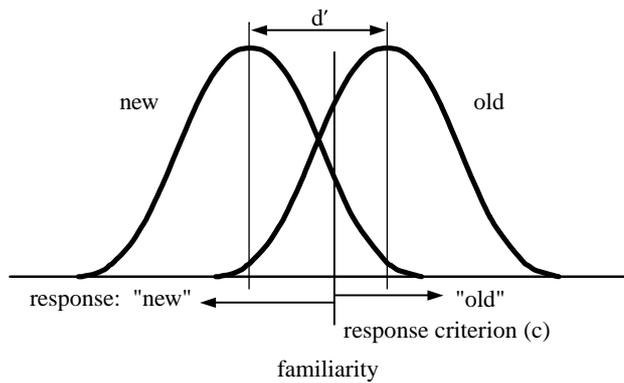
Figure 1. Familiarity distributions for old and new items for an equal-variance signal-detection model.

Figure 2. Symmetrical (lower function) and asymmetrical (upper function) receiver operating characteristics.

response confidence. For example, after studying a list of words, subjects are presented with a mixture of old and new words and are required to make recognition judgements on a scale ranging from 'sure it was studied' to 'sure it was not studied'. The ROC is plotted as a function of confidence such that the leftmost point includes only the most confidently recognized items and subsequent points include less and less confident responses.

Figure 2 shows two hypothetical recognition memory ROCs. The lower function is generated by the signal-detection model illustrated in figure 1. The function is produced by plotting the hits against the false alarms as the response criterion is varied. This function is curvilinear and symmetrical along the diagonal. It is curvilinear because of the continuous nature of the Gaussian familiarity distributions, and it is symmetrical because the old and new item's familiarity distributions are the same shape (i.e. they have equal variance).

Early memory studies indicated that recognition memory ROCs were curvilinear and approximately symmetrical (e.g. Murdock & Dufty 1972). This lent support to the notion that episodic memory reflected only a single component, and justified the practice of measuring recognition accuracy using a single parameter (e.g. d', A', or proportion correct). However, subsequent studies demonstrated that recognition ROCs were not generally symmetrical but rather took the form of the top function in figure 2. The ROC is curvilinear but it is asymmetrical, and appears to be pushed up along the left y-axis. In terms of signal-detection theory, this asymmetry indicates that the old item familiarity distribution must be associated with more variance (i.e. a fatter distribution) than the new item distribution.

The fact that ROCs are asymmetrical is not necessarily a problem for single component views of recognition memory. For example, if the degree of asymmetry were always the same, then one could assume that the old item variance was always some constant amount greater than the new item variance, and thus it would still be possible to measure recognition accuracy using a single d' parameter. Alternatively, if the degree of asymmetry were directly related to accuracy (e.g. as accuracy increased, the degree of asymmetry always increased) then one could still measure recognition performance using a single accuracy parameter.
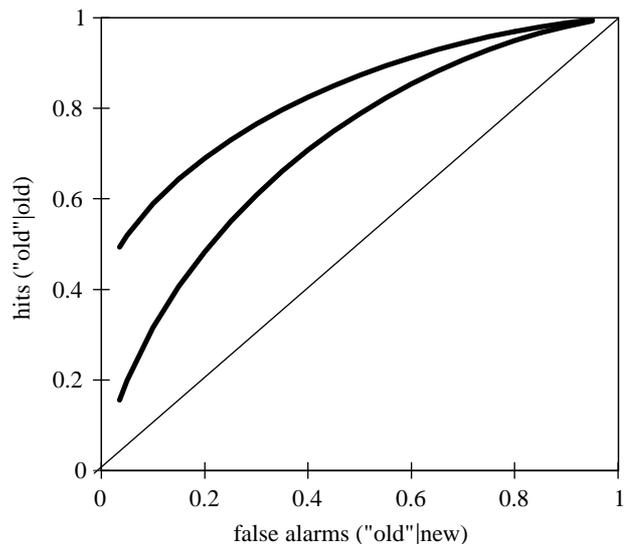
However, recognition accuracy and the degree of ROC asymmetry are functionally independent (e.g. Ratcliff *et al.* 1992; Glanzer *et al.* 1999; Yonelinas 1994), indicating that recognition memory reflects at least two separate memory components. That is, in some studies, increases in accuracy are accompanied by increases in ROC asymmetry, whereas in other studies the degree of ROC asymmetry remains relatively constant as accuracy increases. Thus, there is no way to characterize the existing ROCs using fewer than two separate memory components or parameters.

Using the signal-detection framework, one needs one component to account for increases in accuracy (i.e. d') and another component to account for the changes in ROC asymmetry (i.e. the variance of the old item distribution relative to the new item variance). This 'unequal-variance signal-detection model' can produce the data pattern just described but, as we will see later, it fails to account for the ROCs observed in recognition memory tests.

This simple pattern of results turns out to be extremely problematic for current single process models, even multiple parameter models such as MINERVA and TODAM. The models either predict that the ROC asymmetry should always remain constant or that it should always increase as accuracy increases and thus they cannot account for the fact that both patterns are observed. The problem is that these models do not have separate parameters that are tied to accuracy and ROC asymmetry and it is not possible to introduce separate components without restructuring these models (see Ratcliff *et al.* 1992).

3. THE DUAL-PROCESS SIGNAL-DETECTION MODEL

The important question arising from the ROC literature is, 'why are these dissociations observed in simple recognition memory tests?'. The explanation provided by dual-process theory is that the dissociations occur because there are two retrieval processes, rather than just

one, that contribute to recognition performance. That is, recognition memory judgements can be based either on the assessment of familiarity or on a recollection process whereby subjects retrieve qualitative information about a study event. I will argue that the familiarity process produces an ROC that is curvilinear and symmetrical, whereas the recollection process leads the ROC to become asymmetrical. Because the relative contributions of recollection and familiarity can vary, accuracy and ROC asymmetry can vary independently.

These assumptions form the basis of a simple quantitative model that I will refer to as the dual-process signal-detection model. The model assumes that familiarity is well described by the classical signal-detection model illustrated in figure 1 (i.e. an equal-variance model). In contrast, recollection is assumed to reflect a fundamentally different form of memory retrieval—a threshold retrieval process. Describing recollection as a threshold process means that for any given item a subject either succeeds at retrieving some information about the study event or they fail to. That is, for some items they may retrieve information about when or where the item was presented, but there will be some items that fall below the threshold, and for these items subjects will be unable to retrieve any accurate qualitative information about the study event.

If performance relies exclusively on familiarity then the model predicts a curvilinear ROC that is symmetrical along the diagonal (e.g. the lower function in figure 2 that is generated by an equal variance signal-detection model). If subjects recollect some proportion of the studied items then this will increase the hit rate and influence the shape of the ROC. However, in order to know exactly how it will influence the ROC it is necessary to make assumptions about how recollection and familiarity combine. The model assumes that the two processes make independent contributions to recognition, and that recollection leads to relatively high confidence recognition responses. Thus recollection will add high confidence hits, and the leftmost point on the ROC will move up. Because the ROC is cumulative across confidence, the entire ROC will be shifted up and thus become asymmetrical (e.g. the top function in figure 2).

The model can be represented by the following equations:

$$P(\text{'old'}|\text{old}) = R + (1 - R)F_o \qquad (3.1)$$

$$P(\text{'old'}|\text{new}) = F_n \qquad (3.2).$$

Old items will be correctly recognized if they are recollected (R), or if they are familiar (F_o) in the absence of recollection ($1-R$). New items will be incorrectly accepted as old if they are familiar (F_n). If familiarity is assumed to reflect a signal-detection process then F_o and F_n will be a function of d′ (the distance between the means of the old and new item distributions) and c (the response criterion), such that $F_o = \Phi(d'/2 - c)$ and $F_n = \Phi(-d'/2 - c)$. These functions represent the proportion of the old and new item distributions that exceed the response criterion given that the distance between the means of the two normal distributions is d′ (see Macmillan & Creelman 1991). The model requires two free memory parameters to generate an ROC; R, which

represents the probability that a studied item is recollected, and d′, which represents the average increase in familiarity associated with studying an item.

Given that there are two processes that differentially contribute to the shape of the recognition ROC, the dual-process model can account for the observed dissociations between accuracy and asymmetry. That is, according to the model the asymmetry typically seen in recognition ROCs reflects the fact the recollection is contributing to performance. If recollection increases and familiarity remains relatively constant then accuracy should increase and the ROC should become more asymmetrical. Thus the model can account for cases in which increases in accuracy are accompanied by increases in ROC asymmetry (e.g. Donaldson & Murdock 1968). The model can also account for cases in which increases in accuracy do not influence the degree of asymmetry (e.g. Ratcliff *et al.* 1992). That is, if recollection and familiarity increase approximately equally then the increase in asymmetry caused by recollection will be offset by the increase in symmetry caused by additional familiarity (see Yonelinas 1994 for an illustration of these predictions).

Further support for the model comes from the finding that the shape of the recognition ROC is directly related to the contribution of recollection and familiarity. For example, Jacoby's process dissociation procedure (Jacoby 1991) was used to estimate the contribution of recollection and familiarity, in order to determine the relationship between the shape of the ROC and the contribution of these two processes (Yonelinas 1994). Subjects were required to make both recognition confidence judgements, and list discrimination judgements indicating from which of two study lists the test items originated. The confidence responses were used to plot ROCs. Recollection was then estimated as the ability to determine list membership accurately and familiarity was estimated as the probability of recognizing an item, given that it was not accurately recollected. As expected, the results across several experiments showed that when recollection increased but familiarity was unchanged, accuracy increased while the ROCs became more asymmetrical. Moreover, when both recollection and familiarity increased together, accuracy increased while the ROC asymmetry remained constant. Finally, estimates of recollection and familiarity derived from the process dissociation procedure were found to predict the observed recognition confidence ROCs accurately. The results indicate that the shape of recognition ROCs is directly related to the contribution of recollection and familiarity.

The dual-process model can therefore account for the existing recognition memory ROC results that are problematic for earlier models, and it shows that the shape of the recognition ROC is directly related to the contribution of recollection and familiarity. Although these results provide support for the model, one would like to be able to test the individual assumptions underlying the model directly. One advantage of the model is that it is based on a relatively small number of assumptions, and thus it is possible to assess each of these assumptions in turn. The model assumptions are: (i) recollection is a threshold process; (ii) familiarity is a signal-detection process; (iii) recollection supports relatively high confidence recognition responses; and (iv) these two processes are independent.
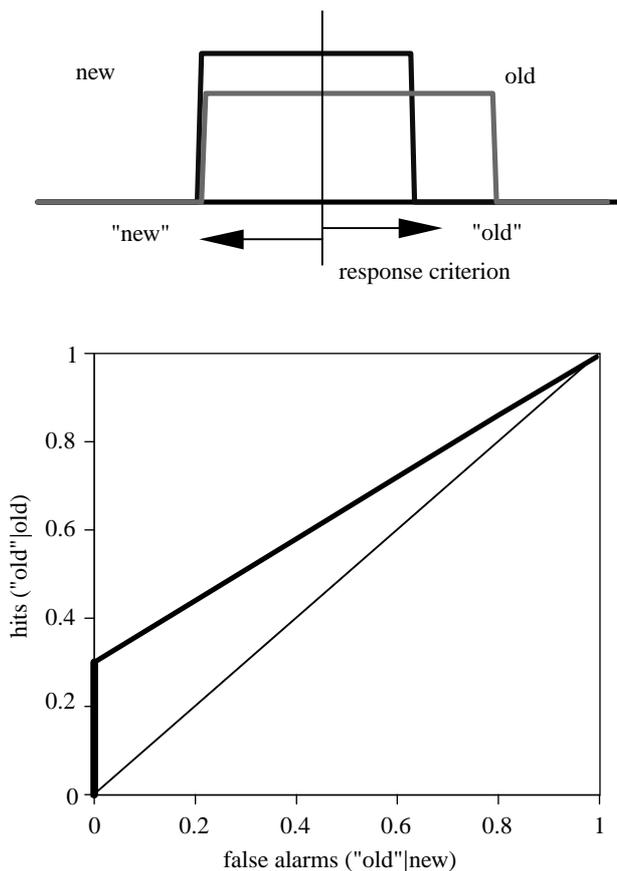
Figure 3. Strength distributions of a high threshold model and the predicted ROC if performance relies exclusively on this threshold process.

Next, I will review the studies that have directly assessed these assumptions.

4. DOES RECOLLECTION REFLECT A THRESHOLD PROCESS?

If recollection is a threshold process, then subjects either retrieve qualitative information about a previous study event or they fail to. They can, of course, retrieve different aspects of an event or different amounts of information, but if they relax their response criterion below the recollective threshold, accurate levels of recollection will not increase. Figure 3 illustrates the strength distributions of a high threshold model and the predicted ROC if performance relies exclusively on this threshold process. The ROC is generated by moving the response criterion from the right to the left along the strength continuum and accepting the items to the right of the response criterion as having been studied. The threshold is the point at which the new item distribution ends (i.e. the right side of the new item distribution). Note that threshold models with more than a single threshold may be appropriate under some conditions (e.g. Yonelinas 1997), but this single threshold model appears to be sufficient to describe recollection in standard recognition paradigms. The recollection distributions are discrete or square rather than continuously varying, thus, unlike signal-detection theory, the model generates a linear ROC. However, note that, strictly speaking, the predicted
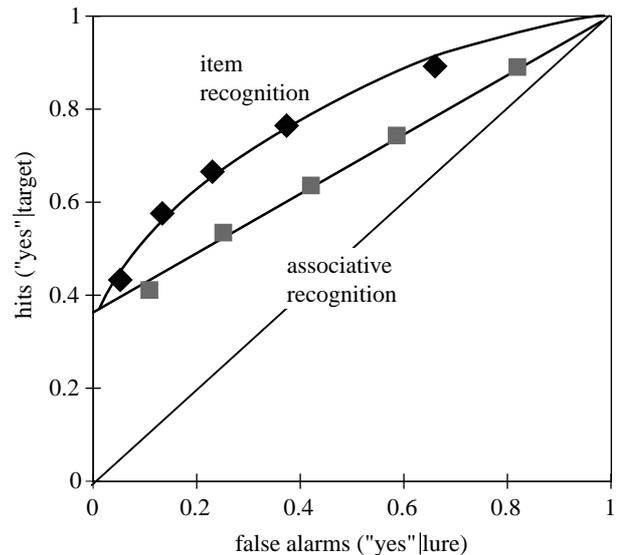

Figure 4. Recognition memory ROCs for item and associative information (Yonelinas 1997, experiment 1).

ROC is actually a kinked line; when the response criterion moves to the right of the threshold, the ROC intersects the *y*-axis and drops. However, as long as the subject places each of their response criteria at—or to the left of—the threshold, the ROC should be a straight line.

One way of determining whether recollection reflects a threshold process is to look for tests of recognition that rely primarily on recollection and determine whether linear ROCs are obtained. Five years ago, it seemed that this assumption must be incorrect because the previous 20 years of recognition memory research had not produced a single linear ROC. However, these studies almost always examined only standard old–new recognition judgements, tests in which familiarity could be used to discriminate between studied and non-studied items.

In order to test the threshold assumption it is necessary to find experimental conditions under which familiarity plays only a limited role in recognition performance. Such conditions were found in tests of associative recognition, in which subjects studied pairs of words and were then required to discriminate between previously presented pairs and rearranged pairs (Yonelinas 1997). Because all the studied and rearranged pairs consisted of familiar items (i.e. they had been studied), familiarity was expected to be less useful than in tests of single item recognition in which the studied items were familiar and the non-studied items were novel. If associative recognition relies primarily on recollection, then the ROCs should be relatively linear. Figure 4 presents the average ROCs for associative and single item recognition (from Yonelinas 1997, experiment 1). Unlike the curvilinear item ROC, the associative ROC is relatively linear. The same results were found in two other experiments in that study and similar results have since been reported using a variety of different materials (e.g. Kelley & Wixted 1998; Rottello *et al.* 2000; Yonelinas *et al.* 1999*b*).

The threshold assumption was further verified in tests of source memory (Yonelinas 1999*a*), in which subjects were required to discriminate between items that had

originated from two different sources (e.g. words spoken by two different experimenters and words presented in different locations). Under test conditions in which the familiarity of items from the two different sources were not expected to differ, the ROCs were relatively linear.

The results of these source and associative memory studies are important in providing support for the assumption that recollection reflects a threshold process. Moreover, they indicate that a simple signal-detection model is not consistent with the ROC data, i.e. signal-detection theory always predicts curvilinear ROCs, as long as performance is above chance. Even a two-component signal-detection model that has separate accuracy and variance parameters (i.e. the unequal-variance signal-detection model) cannot generate linear ROCs.

5. DOES FAMILIARITY REFLECT A SIGNAL-DETECTION PROCESS?

A second critical assumption of the dual-process model is that familiarity reflects an equal-variance signal-detection process. The most critical aspect of this model is that the old and new item familiarity distributions are assumed to have equal variance. There is no *a priori* reason why this assumption must be true and there are reasons to think that it might be violated. For example, if there is a great deal of variability in the degree to which studied items increase in memory strength due to encoding, then one would expect the old item distribution to be associated with greater variance than the new item distribution. Alternatively, there may be some upper limit on the familiarity level that an item can reach, and this could lead the variance of the old item distribution to be less than that of the new item distribution.

A way to test the signal-detection assumption directly is to examine recognition performance under conditions in which performance relies exclusively on familiarity. If familiarity reflects a signal-detection process then the ROC should be curvilinear and symmetrical. One way to test this assumption is to examine recognition ROCs in amnesic patients (e.g. patients with medial temporal lobe damage). Because amnesics are unlikely to recollect previous events but are able to make recognition responses based on assessments of item familiarity (Huppert & Piercy 1976; Mandler 1980; Mayes 1988), their ROCs should reflect the contribution of familiarity in the absence of recollection. If the current dual-process model is correct, and amnesics are making their recognition judgements based on familiarity alone, then their recognition ROCs should be curvilinear and symmetrical, in contrast to the asymmetrical functions observed in healthy subjects. This prediction was tested by examining recognition memory for previously studied words in amnesics and healthy control subjects (Yonelinas *et al.* 1998). Figure 5 shows that, in contrast to control subjects who exhibited curved asymmetrical recognition ROCs, the amnesics' functions were curved and symmetrical. Note that even when overall recognition performance was equated between the two groups by decreasing the study duration of the study items for the control subjects, the controls still exhibited asymmetrical ROCs in contrast to the amnesics. Similar results have also been observed when recognition memory for faces was tested (Dobbins
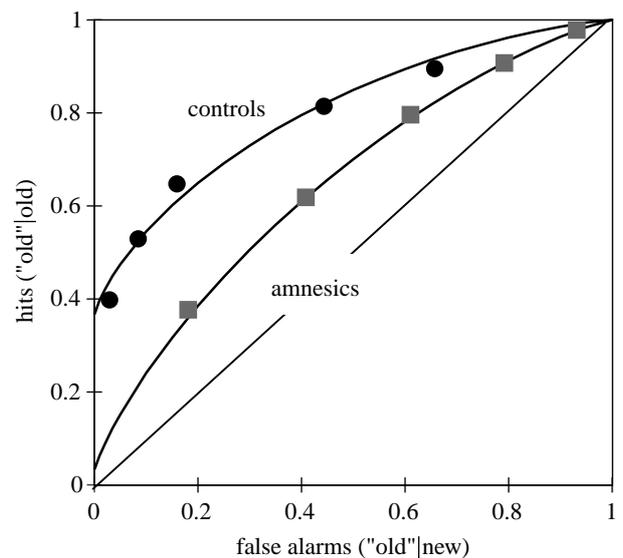
Figure 5. Recognition memory ROCs from amnesics and aged-matched controls (Yonelinas *et al.* 1998).

et al. 1998). These results provide support for the claim that familiarity is well described as an equal-variance signal-detection process, and demonstrate that the model is useful in understanding the memory performance of healthy and memory impaired populations.

Additional support for the threshold and signal-detection assumptions comes from studies using the remember–know procedure (Gardiner 1988; Tulving 1985) to examine the ROCs associated with familiarity and recollection (e.g. Yonelinas 2001). In the remember–know procedure, subjects are instructed to indicate when a recognition judgement is based on recollection (i.e. respond 'remember' if you can recollect any qualitative aspect of the study event) and when it is based on familiarity in the absence of recollection (i.e. respond 'know' if the item is familiar and you know it was studied but you cannot recollect anything about the study event). If subjects are required to make confidence judgements and remember–know judgements for each test item, then remember and know responses can be used to examine separately the ROCs associated with recollection and familiarity.

Figure 6a shows a recognition ROC derived on the basis of confidence judgements (Yonelinas 2001, experiment 1). In agreement with previous studies, the recognition ROC is curvilinear and asymmetrical. Figure 6b shows the separate ROCs for the remembered items and the items accepted on the basis of familiarity. The figure shows that the probability of a remember response remained constant as the response criterion was relaxed, indicating that relaxing the response criterion below the recollection threshold did not lead to an increase in accurate recollection. Familiarity was estimated using the independence remember–know method of analysis (Yonelinas & Jacoby 1995), i.e. because subjects were instructed to respond 'know' whenever an item was familiar but not recollected ($F(1-R)$), familiarity was estimated as the probability of making a 'know' response given that the item was not recollected ($F = K/(1-R)$).
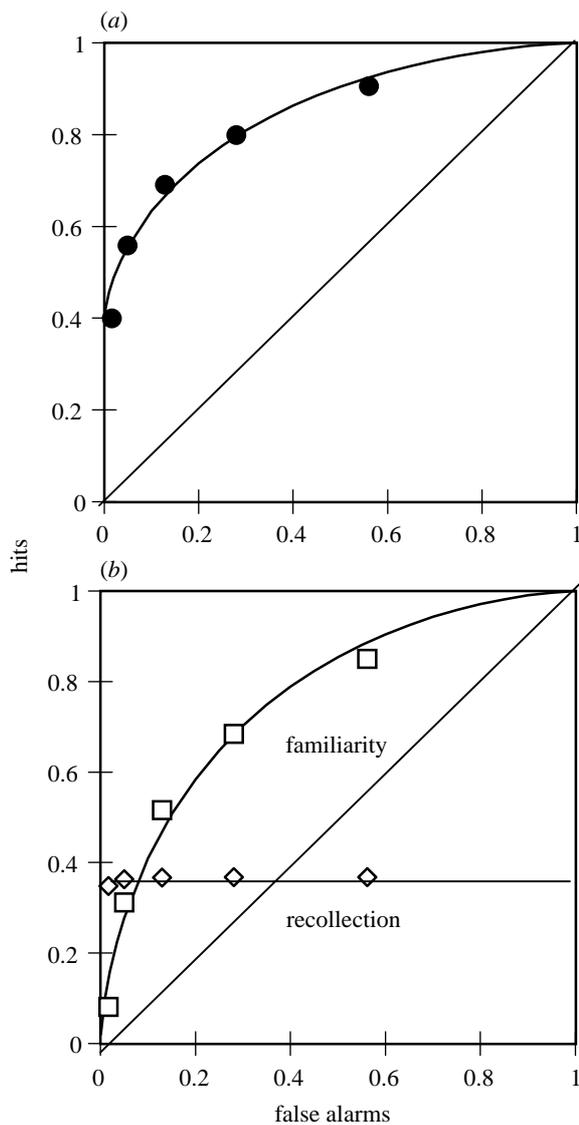
Figure 6. (*a*) Recognition memory ROC, and (*b*) estimates of recollection and familiarity derived from remember–know responses (Yonelinas 2001, experiment 1).

The figure shows that familiarity increased gradually and formed a curved and symmetrical function, as expected if it reflected an equal-variance signal-detection process. Similar results have also been reported using the process dissociation procedure (Yonelinas 1994), i.e. when recollection is estimated as the ability to determine list membership, recollection is found to remain relatively constant as the recognition response criterion is relaxed, whereas familiarity estimates increase gradually and form symmetrical ROCs.

The important point of these studies is that they indicate that the asymmetrical ROCs that are observed in recognition memory tests arise because both recollection and familiarity contribute to performance. When the recollection-based responses are separated from the familiarity-based responses, familiarity is found to behave like a classical signal-detection process (i.e. as the response criterion relaxes, familiarity increases and produces a symmetrical curved ROC), whereas recollection behaves as a threshold process (i.e. recollection remains relatively constant across changes in response criteria).

6. DOES RECOLLECTION SUPPORT RELATIVELY HIGH CONFIDENCE RESPONSES?

A third assumption underlying the dual-process model is that recollection leads to high confidence recognition responses relative to familiarity. This assumption is meant to capture the notion that when subjects retrieve qualitative information about a study event they should be confident that the event actually occurred. In contrast, accepting items on the basis of familiarity should be more error prone because of the overlapping familiarity distributions of old and new items, thus subjects are expected to be less sure about familiarity-based responses than recollection-based responses. The assumption that recollection supports high confidence responses is reflected in the manner in which the two components combine in the dual-process model. That is, the model assumes that response criterion should influence only familiarity while recollection should be relatively invariant as the response criterion is relaxed. The assumption that recollection leads to high confidence responses can of course be violated. For example, if one were to instruct subjects that they would be fined $1000 every time they false alarmed to a new item, they would probably adopt such a strict response criterion that they would respond 'no' to all the familiar items and all the recollected items. The critical question, however, is whether recollection, in general, leads to higher confidence responses than does familiarity.

The results in the remember–know study described earlier suggest that recollection does lead to high confidence responses, i.e. remembered items did not increase appreciably as the response criterion was varied, indicating that recollection did not contribute to the lower confidence responses. However, to assess this assumption more directly it is useful to examine the distribution of recognition confidence responses for remember and know responses. Figure 7*a* presents the proportion of remember and know responses to studied items for each level of recognition memory confidence. It shows that most of the remembered items (94%) led to the highest confidence recognition responses. In contrast, the know responses were distributed across the range of response confidence categories. Note, however, that familiarity based responses were in many cases associated with high confidence responses, and thus confidence in itself cannot be used as an index of recollection and familiarity (for similar arguments, see Gardiner & Java 1990; Rajaram 1993).

Similar results were observed in a study in which subjects made recognition confidence judgements and source memory judgements (i.e. 'was it in list 1 or list 2?') for each test item (Yonelinas 2001). In this study, recollection was measured, not on the basis of subjective reports of remembering but on the basis of accurate source memory, i.e. if the subject can accurately determine when or where the item was studied, it can be assumed that the item was recollected. In this way, accurate source memory was used as an index of recollection. Figure 7*b* shows the source accuracy associated with each level of recognition confidence. It indicates that items receiving recognition confidence scores of less than six were associated with source memory performance that was close to chance (i.e. 50%), whereas items that were recognized
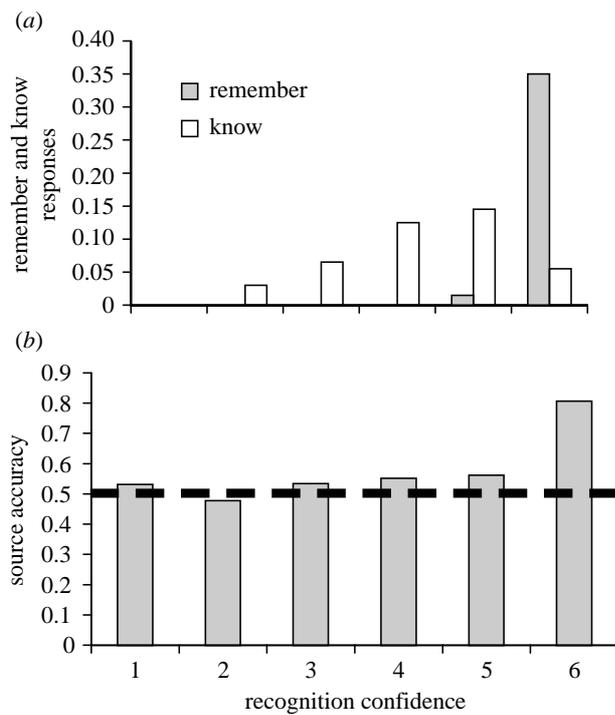
Figure 7. (*a*) The proportion of remember and know responses to studied items for each level of recognition memory confidence (Yonelinas 2001, experiment 1). (*b*) The proportion of studied items leading to correct source judgements for each level of recognition memory confidence (Yonelinas 1999, experiment 3).

with the highest level of confidence were associated with highly accurate source memory judgements.

These studies indicate that whether recollection is measured as 'remember' responses or as the ability to determine source accurately, items that are recollected are associated with high levels of recognition confidence, whereas familiarity based responses are associated with a wide range of confidence responses.

7. ARE RECOLLECTION AND FAMILIARITY INDEPENDENT?

A fourth critical assumption of the dual-process model is that recollection and familiarity are independent retrieval processes. This assumption is supported by numerous behavioural studies indicating that recollection and familiarity are functionally dissociable (for a review see Jacoby *et al.* 1997). For example, several variables such as amnesia, aging, response dead-lining, dividing attention and list length have been found to have disproportionately large effects on recollection compared with familiarity (e.g. Jacoby 1991; Jennings & Jacoby 1993; Toth 1996; Yonelinas 2001; Yonelinas & Jacoby 1994; Yonelinas *et al.* 1998). In contrast, variables such as response bias, massed priming, and study–test lag have disproportionately large effects on familiarity (e.g. Rajaram 1993; Yonelinas 1994; Yonelinas & Levy 2001). It is of course possible to find manipulations that have similar effects on both processes. For example, increasing study duration and varying the size of items between study and test appear to influence both recollection and

familiarity (e.g. Yonelinas 1994; Yonelinas & Jacoby 1995). It is important, however, to realize that these latter findings do not indicate that the two processes are dependent, only that some variables play important roles in both processes.

Other evidence for the independence of recollection and familiarity comes from electrophysiological studies of recognition. For example, remember and know responses are correlated with independent event related potentials (ERPs). In a study of recognition memory for words, knowing responses were found to be associated with an early temporo-parietal positivity in the N400 range and a late fronto-central negativity (Düzel *et al.* 1997). In contrast, remembering responses were associated with a widespread late bifrontal and a left parieto-temporal positivity. Similar recollection and familiarity ERPs have been observed in a study in which recollection was measured as the ability to recollect the plurality of the studied items (Curran 2000), i.e. when subjects were able to determine accurately whether the word was studied in a singular or plural form, a late temporo-parietal positivity was observed. In contrast, familiar items compared with new items, regardless of plurality, led to a early positivity in the N400 range. Although the ERP results do not clearly indicate the brain regions supporting recollection and familiarity, the fact that the recollection and familiarity ERPs are temporally distinct and exhibit distinct scalp topographies suggest that recollection and familiarity rely on partially independent neural generators.

Three recent studies using functional magnetic resonance imaging (fMRI) have provided further evidence that recollection and familiarity involve partially independent brain regions. For example, we examined the temporal lobe regions contributing to recognition memory for line drawings of objects (Yonelinas *et al.* 2001). We found bilateral hippocampal and parahippocampal activation under conditions in which subjects were retrieving associative information accurately about study items (i.e. the colour it appeared in during the study phase), relative to conditions under which they were making accurate item recognition memory judgements (see Figure 8*a*). In contrast, item recognition for previously studied drawings compared with new drawings was not associated with hippocampal or parahippocampal activation but rather was associated with activation in the left inferior temporo-occipital regions (see Figure 8*b*). Thus, hippocampal and parahippocampal regions were involved in the associative test, in which recollection was required, but were not involved in the old item recognition test, in which familiarity was sufficient to discriminate between studied and non-studied items. In an fMRI study examining recognition memory for words, the left hippocampus was associated with greater activation for 'remembered' old words compared with correctly rejected new words, whereas the old words that elicited 'know' responses did not lead to hippocampal activation relative to new items (Henson *et al.* 1999). Remembering and knowing were also found to involve the frontal and parietal cortices differentially in that study, i.e. the left parietal cortex showed greater activation for 'remember' responses while the right lateral and medial frontal cortex showed greater activation for 'know' responses. In another study examining recognition memory for words,
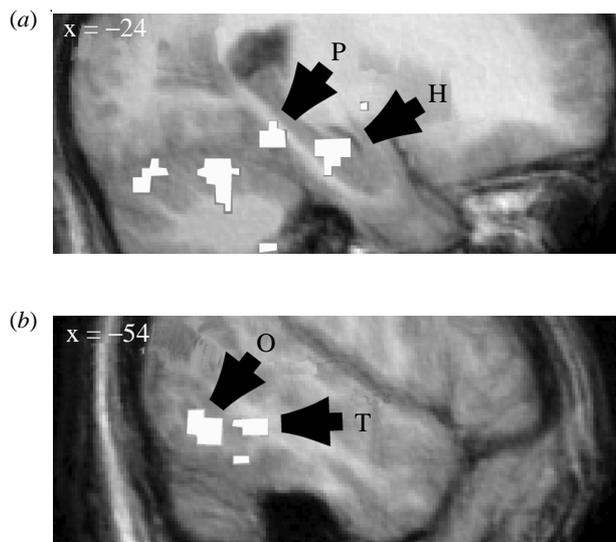
(a)

(b)

Figure 8. Regions of activation overlaid on the average normalized T1 structural images. (a) Bilateral hippocampal [H] and parahippocampal [P] regions were more active during associative recognition than old item recognition (the left hemisphere activations are shown here). (b) Regions in the left middle occipital gyrus [O] and left middle temporal gyrus [T] were more active for old compared with new item recognition.

correct 'remember' responses were associated with increases in hippocampal activation while 'know' responses were not related to increases in hippocampal activation (Eldridge *et al.* 2000).

These neuroimaging studies indicate that the hippocampus is involved in recollection, and they suggest that this region is less important for familiarity. The regions found to be involved in familiarity, however, were less consistent across experiments and future studies are necessary in order to clearly delineate the anatomical substrates of this process. Nonetheless, the fMRI results are clear in showing that the two processes do not rely on identical brain regions, and thus indicate that recollection and familiarity reflect distinct memory retrieval processes.

Taken together, the behavioural, ERP and fMRI results are consistent with the assumption that recollection and familiarity reflect independent memory retrieval processes. However, it seems quite likely that there may be conditions under which these processes interact and future studies that aim to examine such interactions will be extremely useful in developing future models of episodic memory. Still, in light of the evidence supporting the independence assumption, and the dual-process model's success at accounting for the existing recognition memory data, it appears that in general the two processes operate in an independent manner.

8. THE PHENOMENOLOGICAL AND BEHAVIOURAL VALIDITY OF RECOLLECTION AND FAMILIARITY

The dual-process signal-detection model can be used in conjunction with recognition memory confidence results to derive quantitative estimates for the contribution of recollection and familiarity. That is, by fitting the model

equations described earlier to observed ROCs, the model can be used to derive estimates of recollection and familiarity. The method is similar to conducting a linear regression in which one fits a line to the observed data points in order to derive estimates of slope and intercept, but in this case the function is nonlinear and the estimates are of recollection and familiarity (for a detailed description of several fitting methods, see Yonelinas 1999*a*). This method has been used to examine the effects of different experimental manipulations on recollection and familiarity (e.g. Yonelinas 2001) and to determine the fate of these two processes in different patient populations (e.g. Yonelinas *et al.* 1998).

However, one concern that arises when modelling recognition ROCs in this way is that the parameter estimates that are produced may only reflect a convenient mathematical description of the ROC data and they may not capture any real psychological processes. Although it is important that models provide accurate quantitative accounts of existing data, it is equally important that the model's underlying processes are psychologically valid. The validity of these processes can be assessed by asking whether they correspond with other behaviour measures that are expected to index recollection and familiarity. For example, recollection should correspond with the ability to determine where or when an item was presented, and the estimates derived from the ROC analysis should thus parallel those derived from the process dissociation procedure in which recollection is measured as the ability to determine the study source. A related approach is to ask whether these processes have any phenomenological validity. That is, do they correspond to processes that are available to introspective conscious experience. Thus, one can ask whether the estimates derived from the ROC analysis correspond to those derived from the remember–know procedure.

To assess these questions one can examine studies that used the ROC procedure, and either the remember–know procedure or the process dissociation procedure, and plot the estimates derived from the ROC procedure against those derived from the other procedures. If the ROC method produces estimates of recollection and familiarity that converge with those derived from the other methods, it would indicate that the method is accurately characterizing the processes underlying recognition memory. Figure 9 presents estimates for recollection (*a*) and familiarity (*b*) derived from 20 different experimental conditions from four published studies (Yonelinas 1994; Yonelinas 2001; Yonelinas *et al.* 1996; Yonelinas & Jacoby 1995). The bottom axis on each graph represents the estimates derived from the ROC analysis. The vertical axis represents the estimates from the remember–know procedure (top panels) and process dissociation procedure (bottom panels). The top two figures indicate that the ROC and remember–know procedures produce estimates that are almost identical (i.e. the points fall along the diagonal). The bottom figures show that the estimates from the ROC and process dissociation procedure are also quite close. Thus, the estimates from the ROC method converge with estimates derived using the process dissociation and remember–know procedures.

Although the three methods produce estimates that are quite close, it is useful to consider the conditions under
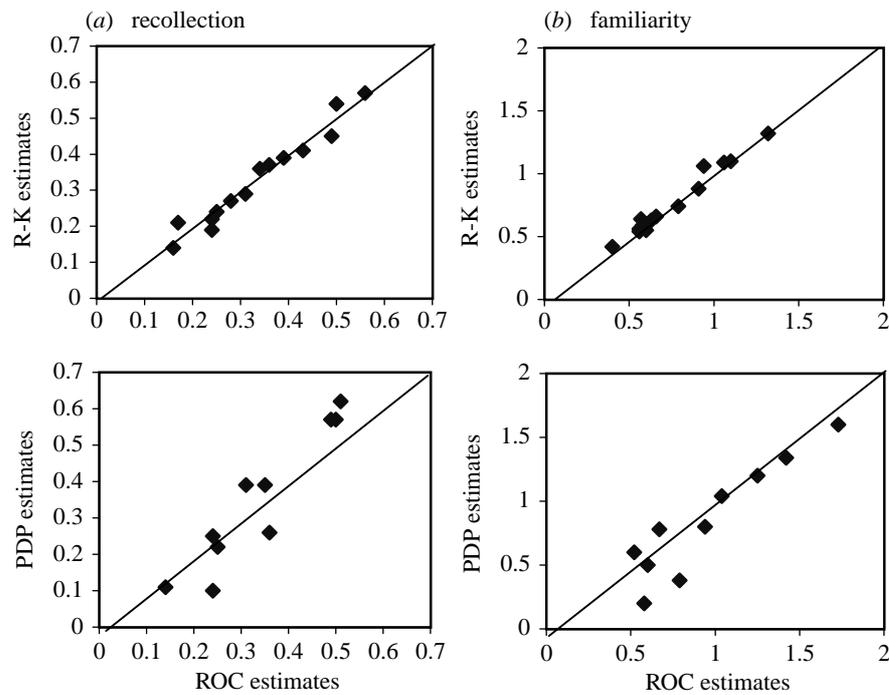
Figure 9. Comparisons of (*a*) recollection and (*b*) familiarity estimates derived from ROC, remember–know and process-dissociation procedures (PDP) (Yonelinas 1994; Yonelinas 2001; Yonelinas *et al*. 1996; Yonelinas & Jacoby 1995).

which the procedures do differ. For example, the two points in the bottom left panel of figure 9 that fall the farthest below the diagonal reflect estimates of recollection derived from a study that used the ROC and process dissociation procedures (Yonelinas & Jacoby 1995). The discrepancy in that study is probably due to the fact that the test conditions in the two tasks were not identical. Most important was that the list discrimination required in the process dissociation task was particularly difficult because the encoding conditions in the two study lists were similar. Because the process dissociation procedure used in that study measured recollection as the ability to discriminate between these two similar lists, the subsequent estimates of recollection were quite low. In contrast, in the ROC confidence procedure, because list discrimination was not required, any information that the subject remembered could be used as a basis for recollection and thus the estimates of recollection were higher. Thus, discrepancies can arise between these different methods of measuring recollection and familiarity when the processes are measured under different conditions. However, there is generally good agreement across the procedures when the conditions are held constant.

The convergence of the results from the three different methods indicates that it is not necessary to plot an entire ROC in order to determine its shape. Rather, asking a subject to make remember–know judgements or source memory judgements appears to provide the same information. Conversely, it does not appear to be necessary to ask subjects to report on the subjective experiences of recollection and familiarity in order to determine the likelihood that subjects will have these conscious experiences. Rather the ROC or process dissociation procedures can be used in conjunction with the dual-process model to predict the occurrence of these conscious states.

The utility of a memory theory is determined in part by its ability to reveal hidden order in otherwise complex datasets. The dual-process model succeeds in doing this by revealing the direct relationship between ROC, process dissociation and remember–know paradigms. It shows that there are two processes, recollection and familiarity, that underlie episodic recognition memory, and that these two processes are responsible for the complex patterns of results that we see in recognition ROCs, tests of associative or source recognition, and in subjective reports of remembering and knowing.

9. MODEL LIMITATIONS

Despite the model's successes, it is quite clear that it is insufficient. Its most obvious limitation is that it is too simple. That recognition memory performance could be accounted for with two or three free memory parameters is extremely unlikely, and there will undoubtedly be cases in which additional processes and alternative assumptions will be required. Preliminary evidence that the model may be too simple comes from studies indicating that it is sometimes found to deviate slightly from the observed recognition ROC data (e.g. Ratcliff *et al*. 1995; Glanzer *et al*. 1999; Yonelinas 1999*b*, 1994). The deviation takes the form that the ROCs are sometimes slightly more curved than the dual-process model predicts. Note that the same problem arises for the unequal-variance signal-detection model as well. However, the observed deviations from the dual-process model are quite subtle: typically the observed points and the points predicted by the model deviate by about 0.01 or 0.02. Nonetheless, these deviations may be important and may indicate that a noise parameter or guessing process is needed (for a discussion of possible explanations

for these deviations, see Ratcliff *et al.* 1994; Yonelinas 1999*b*).

Related issues may arise in tests of associative and source recognition. Although associative and source recognition ROCs can be linear, there are cases in which these ROCs are noticeably curved. One possible explanation for these findings is that a signal-detection process is contributing to these judgements. For example, there may be conditions under which recollection behaves in a more continuous manner, or in which familiarity supports source or associative memory judgements. Preliminary studies have already begun to investigate these issues. For example, one obvious case in which familiarity can support source memory judgements is when one list of items is presented much earlier than another. In this case, subjects may accept the more familiar items as having originated in the more recent list. As expected, source memory ROCs under these conditions tend to be curved (e.g. see Yonelinas 1999*a*).

Familiarity can also contribute to associative memory judgements under some conditions. For example, if associative information is 'unitized' during encoding then familiarity may support associative judgements. That is, if the subject treats two aspects of a study event as a whole unit, or gestalt, then that whole unit, as well as its constituent parts, may become familiar. For example, when subjects are required to discriminate between repeated faces and rearranged faces (e.g. the internal features of a studied face, such as the eyes, nose and mouth, are paired with external features, such as the hair, ears and chin, of another studied face), because each face is treated as a holistic unit (for a review, see Searcy & Bartlett 1996) a repeated face should be more familiar than a mixed face. Thus subjects may make use of familiarity to make the associative memory judgement, leading to curvilinear ROCs. As expected, the associative ROCs under these conditions are found to be curvilinear (Yonelinas *et al.* 1999). Note, however, that when the faces are studied and tested upside down, each face is no longer treated as holistic unit and the resulting associative ROCs are linear.

Familiarity can also support associative memory for word pairs as long as the two words are treated as a single unit. For example, when two words form a compound word (e.g. sea-food, off-shore, ice-cube), repeated word pairs (e.g. ice-cube) are more familiar than new word pairings (e.g. sea-shore) and the resulting ROCs are also curvilinear (J. Quamme & A. P. Yonelinas, unpublished data). The same effects are also observed when the word pairs do not form pre-existing compound words (e.g. sea-cube), as long as the subjects encode the pair as a coherent whole (e.g. at study they are instructed to generate a definition for the novel compound word sea-cube).

These studies indicate that familiarity may be more flexible than was originally thought and that there may be conditions under which it can support recognition judgements previously thought to require recollection. These results are important in reminding us that memory tests should not be treated as direct measures of underlying memory processes (for similar arguments, see Jacoby 1991) and that determining the contribution of recollection and familiarity to memory performance requires careful consideration of the task demands of each memory test.

Probably the most critical limitation of the current model is that it does not specify how memories are represented or how these processes are neurally instantiated. Although it is broadly consistent with some neuro-anatomical models that postulate that recollection and familiarity processes are supported by distinct temporal lobe regions (e.g. Aggleton & Brown 1999; Eichenbaum *et al.* 1994; O'Reilly *et al.* 1997), the neural substrates of recollection and familiarity are not yet known. Careful consideration of neuroanatomy and neurophysiology will be essential in future developments of any episodic memory model.

The approach taken here is to begin with a simple quantitative model and to carefully test the model's assumptions. The idea is that once the basic assumptions are verified and the boundary conditions under which these assumption hold are determined, additional assumptions can be added or the existing assumptions can be modified. This approach differs from the two approaches that have dominated recent cognitive research in memory. One approach has been to propose complex quantitative models that require numerous assumptions about how items are represented and how the retrieval mechanisms work (e.g. the global memory models). The advantage of this approach is that the models make quantitative predictions that can be directly tested. The complexity of these models, however, has in general precluded the possibility of testing their individual assumptions. Moreover, these models have in general focused on behavioural results rather than on neurobiological findings and thus they tend to say very little about the data coming from neuropsychological and neuroimaging studies. An alternative approach that is dominant in cognitive neuroscience studies of memory is to propose general theoretical frameworks that are designed to capture the important distinctions seen in the neuropsychological and neuroimaging literatures. For example, theories proposing distinctions between episodic and semantic memory (Tulving 1983), or between declarative and procedural memory (Squire 1987), have been useful in guiding research and relating human and non-human studies of memory, but because they are generally not quantitative models their predictive power has been limited.

The dual-process model reflects a theory that lies somewhere between these two dominant approaches and I would like to believe that it builds on the strengths associated with each approach. The model is a gross over-simplification of the processes that subjects bring to bear in episodic memory tests. However, the model does provide a very simple and powerful tool for understanding memory performance in a variety of recognition memory paradigms, and it does point to a fundamental distinction between two different types of recognition retrieval processes.

10. CONCLUSIONS

Dissociations observed in recognition memory performance indicate that there are at least two components of episodic memory. A dual-process model that assumes that

subjects can make recognition responses on the basis of independent recollection and familiarity processes is found to be consistent with behavioural, neuropsychological and neuroimaging studies of recognition memory. The results indicate that recollection is well described as a threshold process, whereby qualitative information about previous study events is retrieved, whereas familiarity is well described as a classical signal-detection process, whereby familiar items are accepted as having been studied.

REFERENCES

Aggleton, J. P. & Brown, M. B. 1999 Episodic memory, amnesia and the hippocampal–anterior thalamic axis. *Behav. Brain Sci.* **22**, 425–490.

Atkinson, R. C. & Juola, J. F. 1974 Search and decision processes in recognition memory. In *Contemporary developments in mathematical psychology. Vol. 1. Learning, memory & thinking* (ed. D. H. Krantz, R. C. Atkinson, R. D. Luce & P. Suppes). San Francisco: Freeman.

Clark, S. E. & Gronlund, S. D. 1996 Global matching models of recognition memory: how the models match the data. *Psychon. Bull. Rev.* **5**, 37–60.

Curran, T. 2000 Brain potentials of recollection and familiarity. *Mem. Cognit.* **28**, 923–938.

Dobbins, I., Yonelinas, A. P., Kroll, N. E. A, Soltani, M. & Knight, R. T. 1998 Recognition memory in amnesia and healthy subjects. Paper presented at the *Annual Meeting of the Cognitive Neuroscience Society*, San Francisco.

Donaldson, W. & Murdock, B. B. 1968 Criterion change in continuous recognition memory. *J. Exp. Psychol.* **76**, 325–330.

Düzel, E., Yonelinas, A. P., Mangun, G. R., Heinze, H. & Tulving, E. 1997 Event-related brain potential correlates of two states of conscious awareness in memory. *Proc. Natl Acad. Sci. USA* **94**, 5973–5978.

Eichenbaum, H., Otto, T. & Cohen, N. 1994 Two functional components of the hippocampal memory system. *Behav. Brain Sci.* **17**, 449–518.

Eldridge, L. L., Knowlton, B. J. Furmanski, C. S., Bookheimer, S. Y. & Engel, S. A. 2000 Remembering episodes: a selective role of the hippocampus during retrieval. *Nature Neurosci.* **3**, 1149–1152.

Gardiner, J. M. 1988 Functional aspects of recollective experience. *Mem. Cognit.* **16**, 309–313.

Gardiner, J. M. & Java, R. I. 1990 Recollective experience in word and nonword recognition. *Mem. Cognit.* **18**, 23–30.

Glanzer, M., Kim, K., Hilford, A. & Adams, J. K. 1999 Slope of the receiver operating characteristic in recognition memory. *J. Exp. Psychol. Learn. Mem. Cogn.* **25**, 500–513.

Henson, R. N. A., Rugg, M. D., Shallice, T., Josephs, O. & Dolan, R. J. 1999 Recollection and familiarity in recognition memory: an event-related functional magnetic resonance imaging study. *J. Neurosci.* **19**, 3962–3972.

Hintzman, D. L. 1986 'Schema abstraction' in a multiple trace memory model. *Psychol. Rev.* **94**, 341–358.

Hockley, W. E. 1991 Recognition memory for item and associative information: a comparison of forgetting rates. In *Relating theory and data: essays on human memory in honor of Bennet B. Murdock* (ed. W. E. Hockley & S. Lewandowsky), pp. 227–248. Hillsdale, NJ: Erlbaum.

Huppert, F. & Piercy, M. 1976 Recognition memory in amnesic patients: effects of temporal context and familiarity of material. *Cortex* **12**, 3–20.

Jacoby, L. L. 1991 A process dissociation framework: separating automatic from intentional uses of memory. *J. Mem. Lang.* **30**, 513–541.

Jacoby, L. L. & Dallas, M. 1981 On the relationship between autobiographical memory and perceptual learning. *J. Exp. Psychol. Gen.* **110**, 306–340.

Jacoby, L. L., Yonelinas, A. P. & Jennings, J. M. 1997 The relationship between conscious and unconscious (automatic) influences: a declaration of independence. In *Scientific approaches to the question of consciousness* (ed. J. Cohen & J. W. Schooler), pp. 13–47. Hillsdale, NJ: Earlbaum.

Jennings, J. M. & Jacoby, L. L. 1993 Automatic versus intentional uses of memory: aging, attention, and control. *Psychol. Aging* **8**, 283–293.

Kelley, R. & Wixted, J. T. 2001 On the nature of associative information in recognition memory. *J. Exp. Psychol. Learn. Mem. Cogn.* **27**, 701–722.

Macmillan, N. A. & Creelman, C. D. 1991 *Detection theory: a user's guide.* Cambridge University Press.

Mandler, G. 1980 Recognizing: the judgment of previous occurrence. *Psychol. Rev.* **87**, 252–271.

Mayes, A. R. 1988 *Human organic memory disorders.* Cambridge University Press.

Murdock, B. B. 1982 A theory of storage and retrieval of item and associative information. *Psychol. Rev.* **89**, 609–666.

Murdock, B. B. & Dufty, P. O. 1972 Strength theory and recognition memory. *J. Exp. Psychol. Gen.* **94**, 284–290.

O'Reilly, R. C., Norman, K. A. & McClelland, J. L. 1997 A hippocampal model of recognition memory. *Proceedings of the Neural Information Processing Systems Meeting*, CS7, p. 73.

Rajaram, S. 1993 Remembering and knowing: two means of access to the personal past. *Mem. Cogn.* **21**, 89–102.

Ratcliff, R., Sheu, C. F. & Gronlund, S. D. 1992 Testing global memory models using ROC curves. *Psychol. Rev.* **3**, 518–535.

Ratcliff, R., McKoon, G. & Tindall, M. 1994 Empirical generality of data from recognition memory receiver-operating characteristic functions and implications for the global memory models. *J. Exp. Psychol. Learn. Mem. Cogn.* **20**, 763–785.

Ratcliff, R., Van Zandt, T. & McKoon, G. 1995 Process dissociation, single process theories, and recognition memory. *J. Exp. Psychol. Gen.* **124**, 352–374.

Rotello, C. M., Macmillan, N. A. & Van Tassel, G. 2000 Recall-to-reject in recognition: evidence from ROC curves. *J. Mem. Lang.* **43**, 68–88.

Searcy, J. H. & Bartlett, J. C. 1996 Inversion and processing of component and spatial-relation information in faces. *J. Exp. Psychol. Hum. Percept. Perform.* **22**, 904–915.

Squire, L. R. 1987 *Memory and brain.* New York: Oxford University Press.

Toth, J. P. 1996 Conceptual automaticity in recognition memory: levels-of-processing effects on familiarity. *Can. J. Exp. Psychol.* **50**, 123–138.

Tulving, E. 1983 *Elements of episodic memory.* Oxford University Press.

Tulving, E. 1985 Memory and consciousness. *Can. Psychol.* **26**, 1–12.

Yonelinas, A. P. 1994 Receiver-operating characteristics in recognition memory: evidence for a dual-process model. *J. Exp. Psychol. Learn. Mem. Cogn.* **20**, 1341–1354.

Yonelinas, A. P. 1997 Recognition memory ROCs for item and associative information: evidence for a dual-process signal-detection model. *Mem. Cogn.* **25**, 747–763.

Yonelinas, A. P. 1999*a* The contribution of recollection and familiarity to recognition and source memory judgments: a formal dual-process model and an ROC analysis. *J. Exp. Psychol. Learn. Mem. Cogn.* **25**, 1415–1434.

Yonelinas, A. P. 1999*b* Recognition memory ROCs and the dual-process signal detection model: comment on Glanzer,

Kim, Hilford and Adams (1999). *J. Exp. Psychol. Learn. Mem. Cogn.* **25**, 514–521.

Yonelinas, A. P. 2001 The three Cs of recognition memory: consciousness, control and confidence. *J. Exp. Psychol. Gen.* (In the press.)

Yonelinas, A. P. & Jacoby, L. L. 1994 Dissociation of processes in recognition memory: effects of interference and of test speed. *Can. J. Exp. Psychol.* **48**, 516–534.

Yonelinas, A. P. & Jacoby, L. L. 1995 The relation between remembering and knowing as bases for recognition: effects of size congruency. *J. Mem. Lang.* **34**, 622–643.

Yonelinas, A. P. & Levy, B. 2001 Dissociating familiarity from recollection in human recognition memory. (Submitted.)

Yonelinas, A. P., Dobbins, I., Szymanski, M. D., Dhaliwal, H. S. & King, L. 1996 Signal-detection, threshold, and dual-process models of recognition memory: ROCs and conscious recollection. *Conscious. Cogn.* **5**, 418–441.

Yonelinas, A. P., Kroll, N. E. A., Dobbins, I. G., Lazzara, M. & Knight, R. T. 1998 Recollection and familiarity deficits in amnesia: convergence of remember/know, process dissociation, and ROC data. *Neuropsychology* **12**, 323–339.

Yonelinas, A. P., Kroll, N. E. A., Dobbins, I. G., Soltani, M. 1999 Recognition memory for faces: when familiarity supports associative recognition judgments. *Psychonom. Bull. Rev.* **6**, 654–661.

Yonelinas, A. P., Hopfinger, J. B., Buonocore, M. H., Kroll., N. E. A., & Baynes, K. 2001 Hippocampal, parahippocampal and occipital-temporal contributions to associative and item recognition memory: An fMRI study. *Neuroreport* **12**, 2001.