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Dual-Process Models of the Remember/Know Paradigm

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Dual-process models of the remember/know paradigm are analyzed as consisting of two interrelated components - a process theory and a task theory. A process theory is concerned with the relationship between experimental variables and hypothetical constructs of the model. A task theory is concerned with the relationship between these constructs and the observed proportions of remember and know responses. Three different task theories of the remember/know paradigm are compared - the independence, redundancy, and exclusivity variants. The exclusivity model is shown to be logically inconsistent and three alternative versions are proposed including one based on the principles of fuzzy logic. The resulting six models are compared against existing data under the assumption that remember and know responses are based on the two processes of recollection, selectively affected by variation in age, level of processing, and divided attention, and familiarity, selectively affected by variation in stimulus modality. Data from 22 studies comprising 37 comparisons of age, level of processing, and divided attention are consistent with the independence and fuzzy logic models and inconsistent with the exclusivity and redundancy models. Data from three studies comprising six comparisons of stimulus modality fail to adjudicate between the models. The implications of these results for theories of the remember/know paradigm are discussed.

The remember/know or RK paradigm was introduced by Tulving (1985) to assess hypothetical states of awareness during memory retrieval. The procedure requires subjects to identify the basis on which an item is recognized or recalled. If recognition or recall is accompanied by conscious recollection of details of the prior study episode, a “remember” or R response is made. If recognition or recall is not accompanied by such details, a “know” or K response is made. Research employing the RK paradigm has established that the proportion of remember responses and the proportion of know responses are functionally independent in the sense that “all possible relations between these two states of awareness have been observed” (Gardiner, Ramponi & Richardson-Klavehn, 1998, p.2). That is, there exist variables that affect only R responses, variables that affect only K responses, variables that affect both R and K responses in the same direction, and variables that affect both responses in opposite directions (for reviews see Gardiner, 2000; Gardiner & Richardson-Klavehn, 2000; Richardson-Klavehn, Gardiner & Java, 1996).

Although remember and know responses have been shown to be functionally independent, there has been little consensus concerning how they should be interpreted and understood. One debate concerns the distinction between single and dual-process models. Single-process models, derived from the theory of signal detection, view R and K responses as the consequences of different levels of confidence that an item has been recalled or recognized. Models of this sort have been proposed by Donaldson (1996), Hirshman (1998), and Inoue and Bellezza (1998). Dual-process models view R and K responses as the consequences of two qualitatively different processes or states underlying memory retrieval. Several models of this kind have been proposed (e.g., Gardiner & Parkin, 1990; Knowlton & Squire, 1995; Rajaram & Roediger, 1997; Yonelinas & Jacoby, 1995).

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Drawing on Tulving's (1985) original suggestion, Gardiner and his coworkers have proposed a dual-process model in which remember responses directly reflect a state of consciousness called *autonoetic awareness* while know responses directly reflect an alternative stated called *noetic awareness* (e.g. Gardiner, 2000; Gardiner, Ramponi, & Richardson-Klavehn, 1998; Gardiner & Richardson-Klavehn, 2000). Similar arguments have been proposed by Rajaram and her coworkers (e.g., Rajaram, 1999; Rajaram & Roediger, 1997). On this view, variables that affect R responses may be interpreted as affecting the probability that memory retrieval involves autonoetic awareness, while variables that affect K responses may be interpreted as affecting the probability that memory retrieval involves noetic awareness. Since R and K responses are mutually exclusive, this view has been called the *exclusivity model* of the remember/know paradigm (Gardiner & Parkin, 1990). In contrast, Jacoby and his coworkers have proposed that R and K responses are based on the products of two independent processes of memory retrieval, called *recollection* and *familiarity* (e.g. Jacoby, Yonelinas & Jennings, 1997; Yonelinas & Jacoby, 1995). On this view, R responses depend on recollection while K responses depend on familiarity in the absence of recollection. This proposal is called the *independence model* of the remember/know paradigm. In contrast to these models, Knowlton and Squire (1995) have proposed that R responses index a memory process whose operation is dependent on a more basic memory process subserving K responses. This view is called the *redundancy model* of the remember/know paradigm.

Single and dual-process models represent incompatible accounts of remember and know responses (Gardiner, 2000). Although this debate is not yet resolved, attention has recently been focused on a further debate within the class of dual-process models concerning the nature of the processes or states thought to underlie R and K responses, how these processes are affected by different experimental variables, and how they each serve to determine the observed proportions of R and K responses. This debate is important because it raises issues that are relevant to dual-process models of memory in general (Jacoby, 1983, 1991). In particular, it concerns the question of how observable measures of memory performance can be used to identify and help characterize the nature of the hypothetical memory processes. If the relationship between remember and know responses and the processes or states they are assumed to index is unknown, then the results of experiments investigating these responses will be uninterpretable. At the present time in many cases, one or other of the three dual-process models is simply assumed and the data interpreted accordingly. This practice has naturally led to considerable uncertainty concerning the meaning and significance of remember and know responses (e.g., Mangels, Picton & Craik, 2001). In order to resolve this problem, it is necessary to devise a research strategy through which different dual-process models can be evaluated empirically. The aim of the present paper is to outline and implement such a strategy.

Existing dual-process models of the RK paradigm can be analyzed as consisting of two interrelated components; a *process theory* and a *task theory*. This distinction was introduced by Dunn and Kirsner (1989) to clarify the relationship between a model's description of underlying hypothetical constructs (processes) and the observable measures of these constructs (tasks). A process theory describes how different experimental variables affect the hypothetical constructs postulated by a model, while a task theory describes how these constructs affect the particular measure or measures of interest which, in the case of the RK paradigm, concern the proportions of R and K responses.

Although logically distinct, process and task theories are naturally connected. In part, this is due to the fact that each theory refers to the same set of hypothetical constructs. This constrains the kinds of process and task theories that can be proposed. For example, in the model of the RK paradigm proposed by Jacoby et al. (1997), the hypothetical constructs are identified with the same processes of recollection and familiarity that have been proposed to account for the results of experiments using the process-dissociation procedure (Jacoby 1991; Kelley & Jacoby, 2000). On this view, recollection is characterized as slow, intentional, and attention-demanding, while familiarity is characterized as relatively fast, automatic, and having low demands on attention. In the light of these descriptions, it is possible to identify several variables, such as age, level of processing, and divided attention at study, that should selectively affect recollection and another set of variables, such as habit strength and changes in study-test format, that should selectively affect familiarity. This characterization of the two processes and the variables that affect them constitutes the process theoretical part of the model. In addition, recollection and familiarity are assumed to be independent of each other which means that they determine R and K responses in a particular way. The description of this relationship constitutes the task theoretical part of the model.

The process and task theoretical components of a model are also connected in a second, more subtle, way. Although it is necessary to specify both kinds of theory in order to provide a complete account of the phenomenon of interest, it is logically impossible to test both theories simultaneously. In order to determine which of several process theories is correct, it is necessary to know the correct task theory. But, in order to determine which task theory is correct, the correct process theory must also be known. This dependence can be illustrated with reference to a study by Rajaram (1996). The aim of this study was to test a particular dual-process model of the RK paradigm, namely that "Conceptual manipulations selectively influence Remember judgments (or the recollective component of memory), and perceptual manipulations selectively affect Know judgments (or the familiarity component)" (Rajaram, 1996, p.366). Embedded in this statement is a process theory and a task theory. The process theory states that conceptual manipulations affect one of the two hypothetical constructs, namely the recollective component of memory, while perceptual manipulations affect the other hypothetical construct, namely the familiarity component of memory. The task theory specifies how these constructs determine the measures of interest. It states that Remember judgments depend on the recollective component and Know judgments depend on the familiarity component. Rajaram (1996) conducted three experiments that each varied a different perceptual property of targets between study and test in a recognition memory task. The results were clear. In each experiment, a change in the relevant perceptual property reduced the proportion of R responses. Consequently, it was concluded that R responses do not depend upon the recollective component of memory. That is, the process theory that the construct underlying R responses is unaffected by perceptual manipulations was rejected. However, this conclusion depends upon the assumption that the proposed task theory is correct. If R responses depend upon *both* the recollective and familiarity components of memory, then the data may not be inconsistent with the candidate process theory. That is, instead of assuming the task theory to be true and rejecting the process theory, it is equally valid to assume that the process theory is correct and to use the results of the three experiments to refute the task theory[2].

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[2] In general it is always possible to generate a task theory that leaves the process theory intact. To illustrate, let r be the probability that an item is recollected and let f be the probability that it is familiar. Then the data from all three experiments by Rajaram (1996) are well described by the relationship,

Debate concerning the interpretation of remember and know responses turns on both process and task theories. As mentioned above, several different task theories have been proposed for the RK paradigm. In addition, several different process theories have also been proposed. In their recent review, Gardiner and Richardson-Klavehn (2000) discussed three such theories, although each was predicated on the task theory defined by exclusivity model. The first process theory is the proposal by Tulving (1985) that the construct underlying remember responses reflects retrieval from episodic memory while the construct underlying K responses reflects retrieval from semantic memory. On this view, variables that selectively affect the formation of episodic memories should only affect R responses while variables that selectively affect the formation of semantic memories should only affect K responses. The second process theory is the proposal by Rajaram (1996), mentioned above, that the construct underlying R responses reflects recollection while the construct underlying K responses reflects familiarity. The third process theory is a more recent proposal by Rajaram (1996, 1998) that the construct underlying R responses reflects the distinctiveness of processing, whether conceptually or perceptually based, while the construct underlying K responses reflects fluency of processing, which may also be either conceptually or perceptually based. Clearly, the interpretation of evidence as either for or against each of these accounts depends upon the task theory that is assumed. Consequently, it is impossible to resolve the question of which process theory of the RK paradigm is correct without first resolving the question of which task theory is correct.

Since all dual-process models of the remember/know paradigm agree on the number of constructs underlying R and K responses, it is logically possible to combine each possible process theory with each possible task theory. While this could, in principle, lead to an indefinite number of models, in practice several limits can be placed on the range of possible theories. For example, task theories ought not to be generated *ad hoc* simply to explain a particular set of results. Instead they should be well motivated in the sense that they can be derived from some acceptable *a priori* propositions. They should also be expected to meet some basic criteria of logical consistency. That is, they should not predict outcomes that are logically impossible. Limits can also be placed on the range of possible process theories. The most important of these concerns the principle of parsimony. That is, it is unlikely that the hypothetical constructs underlying R and K responses are unique to the remember/know paradigm. Rather, parsimony dictates that the process theory relevant to this paradigm should also be relevant to other tasks and paradigms involving human memory.

Considerations such as the foregoing suggest the following research strategy. First, the set of possible task theories for the RK paradigm should be identified and evaluated against a criterion of logical consistency. Second, a candidate process theory should be assumed and the predictions of the resulting combined dual-process models evaluated against existing or newly gathered data. If any model provides a satisfactory fit to the data, it would constitute a viable account of the RK paradigm. If, on the other hand, none of the models in question provides a satisfactory fit to the data, one of two possible conclusions could be drawn. The first is that the candidate process theory is correct but that none of the task theories is correct. In this case, it would be necessary to identify and to evaluate alternative task theories, bearing in mind that it is always possible to generate a task theory *ad hoc* that will account for any data. The second conclusion is that the candidate process theory is incorrect. In this case, an

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$R = (rf^2 - 2rf + r)/(f^2 - 2rf + r)$ and $K = f$, under the constraint that r varies between experiments but does not vary within an experiment (i.e. is unaffected by the relevant perceptual manipulation).

alternative process theory can be proposed and the entire procedure repeated. The aim of the present study is to implement this strategy in order to evaluate current dual-process models of the RK paradigm.

The remainder of the paper is divided into three main parts. In the first part, the set of task theories that have been proposed in the context of existing dual-process models of the RK paradigm are identified. It is shown that the exclusivity model is logically inconsistent in the sense that it predicts outcomes that are impossible. In order to overcome this problem, three alternative formulations of exclusivity are explored. Two of these are shown to have additional conceptual difficulties, but a third, based on the principles of fuzzy logic, overcomes each of these problems. Each of the resulting set of six task theories is then given an explicit mathematical form from which it is possible derive a unique set of *isometric contours*. These contours correspond to the outcomes predicted by each theory as a consequence of the selective manipulation of one of the two underlying processes. The identification of these contours is crucial to the evaluation of the different task theories in the context of a given process theory. In the second part of the paper, a candidate process theory is assumed, based on the proposal that R and K responses are subserved by the processes of recollection and familiarity. The respective task theories are then evaluated against existing data derived from 26 studies comprising 44 comparisons of variations in age, level of processing, and divided attention, thought to selectively affect recollection, and stimulus modality thought to selectively affect familiarity. In the third part of the paper, the implications of the results of this analysis for existing models of the RK paradigm are discussed.

TASK THEORIES OF THE REMEMBER/KNOW PARADIGM

Models of the RK paradigm account for the effects of different experimental variables on the proportions of remember and know responses. Each is composed of a process theory and a task theory. The process theory describes a mapping from levels of experimental variables onto model parameters representing the postulated processes or theoretical constructs. The task theory describes the mapping from these parameters onto the expected proportions of R and K responses. As a consequence, each task theory can be thought of as specifying a *parameterization* of the surface defined by all possible combinations of the proportions of R and K responses.

Let R be the proportion of remember responses and let K be the proportion of know responses under a given set of experimental conditions. The *RK response surface* is defined as the set of points in which each possible value of R is combined with each possible value of K. This corresponds to the triangular region of two-dimensional vector space enclosed by the three inequalities,

$$\begin{aligned} R &\geq 0 \\ K &\geq 0 \\ R + K &\leq 1 \end{aligned} \tag{1}$$

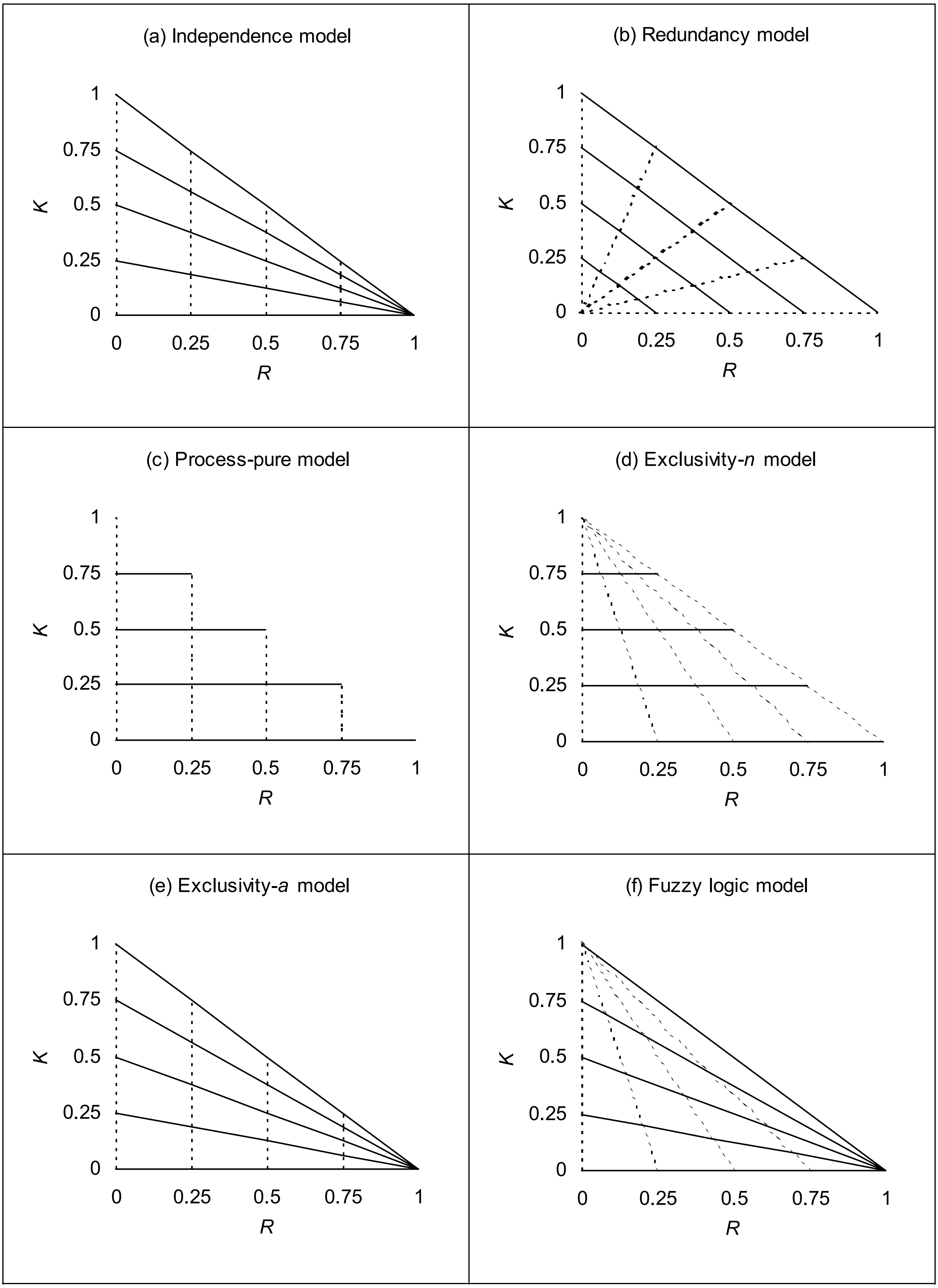
The first two of these inequalities derive from the fact that R and K are proportions and necessarily non-negative. The third inequality derives from the fact that the categories of remember and know responses are mutually exclusive. Consequently, the sum of R and K cannot exceed one.

Each task theoretical component of a dual-process model can be interpreted as a different parameterization of the *RK* response surface. For present purposes, these parameters are labeled by the letters *a* and *n*. While these letters evoke the constructs of *autonoetic* and *noetic* awareness, no commitment is made to this particular interpretation. They have been chosen purely for their mnemonic properties since in each of the task theories to be considered, R responses are positively related to *a* while K responses are positively related to *n*. The values of *a* and *n* are also be assumed to be bounded between zero and one.

The set of all permissible values of *a* and *n* defines a two-dimensional *parameter space*. The predictions of any dual-process task theory are completely determined by the function that maps a point in this space onto a point on the *RK* response surface. A general form of this function is given by the equation,

$$\begin{aligned} R &= f_R\left(a,n\right) \\ K &= f_K\left(a,n\right) \end{aligned} \tag{2}$$

Equation (2) also specifies a set of *isometric contours* on the *RK* response surface. Similar to lines of latitude and longitude on the earth's surface, isometric contours connect points on the *RK* response surface that have the same values for either parameter, *a* or *n*. The shape of these contours is critical for predicting the effect on *R* and *K* of experimental variables that selectively affect the value of one or other model parameter. For example, consider an experimental variable that affects the value of *a* but has no effect on the value of *n*. The result will be a set of points lying on one of the isometric contours of constant *n*. Similarly, if an experimental variable affects the value of *n* but has no effect on the value of *a*, the observed data will lie on one of the isometric contours of constant *a*. Importantly, each one of the following task theories is associated with a different set of isometric contours.


(a) Independence model

(b) Redundancy model

(c) Process-pure model

(d) Exclusivity-*n* model

(e) Exclusivity-*a* model

(f) Fuzzy logic model

Figure 1. Isometric contours for each task theory of the remember/know paradigm.

Independence

According to the independence model, item recognition is based on the products of two independent processes of memory retrieval. In the model proposed by Jacoby et al. (1997), one process involves recovery of details of the study episode, in which case a target is said to be "recollected". The second process, perhaps reflecting increased fluency of processing, leads to the target being "familiar". In terms of equation (2), parameter a is interpreted as the probability that a target is recollected and parameter n is interpreted as the probability that the target is familiar. Since a and n are independent, the probability that a target is both recollected and familiar is given by the product, an. It is also assumed that if an item is recollected, an R response is always made. This is a reasonable assumption given that the task instructions stress that if details of the study episode can be recollected, an R response ought to be made. Consequently, the probability of an R response is equal to the probability that an item is recollected while the probability of a K response is equal to the probability that an item is familiar but not recollected. This relationship is given by the following equation,

$$\begin{aligned} R &= a \\ K &= (1-a)n \end{aligned} \tag{3}$$

The two sets of isometric contours corresponding to equation (3) are shown in Figure 1a. The contours of constant a correspond to the dashed vertical lines while the contours of constant n correspond to the solid diagonal lines radiating from the point, $R = 1$, $K = 0$. The equations for both sets of isometric contours can be derived from the inverse function that maps points from the RK response surface onto points in the parameter space. The two equations are,

$$\begin{aligned} &\text{Constant } a: \quad R - a = 0 \\ &\text{Constant } n: \quad K + n \cdot R - n = 0 \end{aligned}$$

Redundancy

According to the redundancy model, item recognition is based on the products of two processes of memory retrieval, one of which is dependent upon the other. In the model proposed by Tulving (1985) and Knowlton (1998), the first process leads to the retrieval of sufficient information to support a know response while the second process, contingent on the first, leads to the retrieval of sufficient information to support a remember response. In terms of equation (2), parameter n represents the probability that the first process is successful, and parameter a represents the conditional probability that the second process is successful, given successful completion of the first. If it is also assumed that a remember response is always made if the second process is successful, the following equation results,

$$\begin{aligned} R &= an \\ K &= (1-a)n \end{aligned} \tag{4}$$

According to equation (4), any variable that affects a will affect R and K in opposite directions. Conversely, any variable that affects n will affect R and K in the same direction. These effects are summarized by the isometric contours shown in Figure 1b. The equations of these contours are,

$$\begin{aligned}\text{Constant } a: &\quad a \cdot K - (1-a) \cdot R = 0 \\ \text{Constant } n: &\quad K + R - n = 0\end{aligned}$$

In Figure 1b, the contours of constant *a* correspond to the dashed diagonal lines of positive slope radiating from the origin, reflecting the fact that if only *n* changes, *R* and *K* are affected in the same way. The contours of constant *n* correspond to the solid diagonal lines of slope −1, reflecting the fact that a change in *a* affects *R* and *K* in opposite directions.

Exclusivity

According to the exclusivity model, item recognition is based on the products of two mutually exclusive processes of memory retrieval. One process leads to a state of noetic awareness and supports a know response. The other process leads to a state of autonoetic awareness and supports a remember response. In terms of equation (2), parameter *a* is interpreted as the probability of autonoetic awareness, and parameter *n* is interpreted as the probability of noetic awareness. The exclusivity theory was first proposed by Gardiner and Parkin (1990) and, although it has never been given a precise mathematical form, whenever it has been discussed in the literature, the following relationship is generally assumed,

$$\begin{aligned}R &= a \\ K &= n\end{aligned} \tag{5}$$

Equation (5) describes a *process-pure* interpretation of remember and know responses. The set of isometric contours associated with this equation is shown in Figure 1c. The equations of these contours are,

$$\begin{aligned}\text{Constant } a: &\quad R - a = 0 \\ \text{Constant } n: &\quad K - n = 0\end{aligned}$$

In Figure 1c, the contours of constant *a* correspond to the dashed vertical lines and the contours of constant *n* correspond to the solid horizontal lines.

The process-pure exclusivity model is intuitively simple and appears to make the fewest assumptions concerning the relationship between underlying processes and responses. However, its apparent simplicity belies a logical inconsistency. When first proposing this model, Gardiner and Parkin (1990) stated that “exclusivity assumes that the underlying components have no relation with one another, so that the outcome of one component exerts no influence over the other component” (p. 582). This is however a description of independence. If two components are mutually exclusive then they are related to each other in a manner analogous to a negative correlation (Jones, 1987). That is, all things being equal, whenever one component increases the other must decrease. For the independence and redundancy models, exclusivity is a property of the response alternatives and arises in these models as a consequence of the functions that map the parameter values onto response probabilities. The parameters, representing key properties of the underlying components, have no relation to one another[3]. In contrast, in the process-pure interpretation, it is assumed that the parameters enter into a relationship by being mutually exclusive. This property of the

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[3] This is true for the redundancy model as long as *a* is interpreted as a conditional probability.

model is both unexplained and serves to create a logical difficulty. Since variables exist that have parallel effects on both remember and know responses (Gardiner, Ramponi & Richardson-Klavehn, 1999; Gardiner & Richardson-Klavehn, 2000), changes in these variables must increase the values of a and n in equation (5). But such correlated increases, unless controlled by an additional mechanism could, in principle, lead to the sum of R and K being greater one, which is impossible. This means that equation (5) is incoherent without the additional constraint that $a+n \le 1$. Yet this is a substantive claim about the relationship between processes represented by the two parameters, which demands an explanation.

A natural way to account for the exclusivity of autonoetic and noetic awareness is to employ a logic similar to that used by the redundancy model. That is, it might be supposed that the process leading to autonoetic awareness is engaged only if the process leading to noetic information is unsuccessful. In this interpretation, n is the probability of noetic awareness, and a is the conditional probability of autonoetic awareness, given that noetic awareness has not occurred. The probability of autonoetic awareness is therefore equal to $a(1-n)$. This variant of exclusivity is called the *exclusivity-n model* and conforms to the following equation,

$$\begin{aligned} R &= a(1-n) \\ K &= n \end{aligned} \tag{6}$$

Figure 1d shows the isometric contours of constant a and constant n derived from equation (6). The equations of these contours are given by,

$$\begin{aligned} &\text{Constant } a: \quad a \cdot K + R - a = 0 \\ &\text{Constant } n: \quad K - n = 0 \end{aligned}$$

Although the exclusivity-*n* model both incorporates an assumption of exclusivity and satisfies the requirement that $R+K \le 1$, it is not the only possible theory of this form. In deriving equation (6), it was assumed that autonoetic awareness was contingent on the absence of noetic awareness fails. An alternative version assumes the converse, namely that noetic awareness is contingent on the absence of autonoetic awareness. In this interpretation, a is the probability of autonoetic awareness and n is the conditional probability of noetic awareness, given that autonoetic awareness has not occurred. In this case, the probability of noetic awareness is equal to $n(1-a)$. This version of exclusivity is called the *exclusivity-a model* and is described by the following equation,

$$\begin{aligned} R &= a \\ K &= n(1-a) \end{aligned} \tag{7}$$

It is immediately apparent that equation (7) is equivalent to the independence model corresponding to equation (3). The only difference between these accounts concerns the substantive interpretation of the two parameters. In equation (7), n is interpreted as a conditional probability while in equation (3), it is interpreted as a simple probability. In every other respect the models are identical. A similar relationship is also true for the exclusivity-*n* model. This model is equivalent to an independence model in which priority is given to a K response when both R and K responses are possible. That is, if it is assumed that whenever the products of both retrieval processes are available (i.e. an item is both recollected and familiar) a K response (instead of an R response) is made. The only difference between this version of independence and the exclusivity-*n* model is again one of interpretation. Whereas in the exclusivity-*n* model, *a* is interpreted as a conditional probability, in the equivalent independence model, *a* is interpreted as a simple probability.

The previous arguments suggest that the exclusivity assumption contains several logical difficulties. Either the theory is incomplete in failing to account for the basic fact of exclusivity, or, if it includes such an account, it is found to be indistinguishable from theories that assume that the processes involved are actually independent. For these reasons, it is of interest to explore an alternative conceptualization of exclusivity based on an idea that appears to have been implicit in original proposal by Gardiner and Parkin (1990), namely that R and K responses are related *symmetrically* to the underlying processes. On this view, R and K responses depend upon two qualitatively different processes or states neither of which may be considered more "basic" nor having higher priority than the other. While the process-pure model is symmetrical in this sense, the independence, redundancy, exclusivity-*a*, and exclusivity-*n* models are all asymmetrical. Symmetry can also be defined in terms of equation (2) by the requirement that, $f_R(a,n) = f_K(n,a)$. For the process-pure model, $f_R(a,n) = a$ and $f_K(a,n) = n$. Therefore, $f_R(a,n) = f_K(n,a)$. This relationship does not hold for any of the other models. Symmetry also implies that transposition of the axes of *RK* response space, to create a "*KR* response space", does not change the shapes of the isometric contours. Inspection of Figure 1c shows that this is also the case for the process-pure model. An alternative conceptualization of exclusivity that is both symmetrical and logically consistent is presented in the next section. For reasons that will become apparent, this model is called the *fuzzy logic model* of the remember/know paradigm.

The fuzzy logic model

Massaro and his co-workers have proposed a general model of perception called the *fuzzy logic model of perception* or FLMP (e.g., Massaro, 1998; Massaro & Friedman, 1990). This model provides a useful framework for constructing a symmetrical theory of the remember/know paradigm since a key feature of the approach is that each response alternative is determined in the same way by the underlying processes.

The principal elements of the FLMP are the three stages of feature evaluation, feature integration, and decision making (Massaro & Cohen, 2000). During feature evaluation, each source of information or stimulus feature is assigned a fuzzy truth values representing the degree to which it supports each of the response alternatives. A fuzzy truth value is a number ranging from zero to one that represents the extent to which a feature is consistent with or supports assignment of the stimulus to the given category or response alternative. A value of one means that category membership is certain, a value of zero means that category membership is impossible, while a value of 0.5 means there is as much information in favor of the category as there is against it. Each source of information is evaluated independently of the others and if a_i is the fuzzy truth value of feature *i* for response alternative *A*, then $(1-a_i)$ is the fuzzy truth value of feature *i* for every other response alternative. In the feature integration stage, the total support for each alternative is calculated by multiplying together its respective fuzzy truth values on each stimulus feature. Let S_A be the total support for alternative *A* and let a_i is the fuzzy truth value of feature *i* for this alternative. Then,

$$S_A = \prod_i a_i$$

In the decision stage, the total support for each response alternative is mapped onto a response probability by dividing it by the sum of all the support given to every alternative in accordance with Luce's choice axiom (Luce, 1959). Let S_j be the total support for response alternative j and let P_j be the probability of this response. Then,

$$P_j = \frac{S_j}{\sum_i S_i}$$

The FLMP framework can be applied to the remember/know paradigm in the following way. First, it is assumed that during memory retrieval two sources of information indicative of prior occurrence are evaluated. It is not necessary for the model to specify the nature of these sources of information but as an example, one source of information may concern access to details of the study episode (i.e., recollection), while the other source of information may concern the ease with which the target was processed at test (i.e., perceptual fluency or familiarity). The two sources of information are then evaluated according to the extent to which they support or are consistent with each response alternative. In the remember/know paradigm there are three response alternatives – remember, know and new. Let a be the fuzzy truth value reflecting the degree to which the first source of information supports a remember response. Then $(1-a)$ is its degree of support for both know and new responses. Let n be the fuzzy truth value reflecting the degree to which the second source of information supports a know response. Then $(1-n)$ is its degree of support for both remember and new responses. This leads to the following three equations describing the total support for each alternative from both these sources of information,

$$\begin{aligned} S_R &= a(1-n) \\ S_K &= (1-a)n \\ S_N &= (1-a)(1-n) \end{aligned}$$

where S_R is the total support for a remember response, S_K is the total support for a know response, and S_N is the total support for a new response. Let R be the probability of a remember response, let K be the probability of a know response, and let N be the probability of a new response. Then,

$$\begin{aligned} R &= S_R / (S_R + S_K + S_N) \\ K &= S_K / (S_R + S_K + S_N) \\ N &= S_N / (S_R + S_K + S_N) \end{aligned}$$

which, following some algebra, leads to the following equation for the fuzzy logic model of the remember/know paradigm,

$$\begin{aligned} R &= \frac{a(1-n)}{(1-an)} \\ K &= \frac{n(1-a)}{(1-an)} \end{aligned} \qquad (8)$$

It is clear that the two functions in equation (8) are symmetrical. That is, $f_R\left(a,n\right)=f_K\left(n,a\right)$. Furthermore, since *a* and *n* correspond to fuzzy truth values bounded by zero and one, equation (8) confines the values of *R* and *K* to points on the *RK* response surface. That is, $R+K\leq 1$. Therefore, the fuzzy logic model overcomes the logical difficulties of the process-pure model and incorporates, in its functional form, an account of the exclusivity of R and K responses.

The equations for the isometric contours of constant *a* and constant *n*, corresponding to equation (8) are given by,

$$\text{Constant } a: \quad a\cdot K+R-a=0$$

$$\text{Constant } n: \quad K+n\cdot R-n=0$$

A set of these contours is shown in Figure 1f.

THEORY EVALUATION

Each of the six task theories illustrated in Figure 1 is consistent with the observed functional independence of remember and know responses. That is, there is no point on the triangular *RK* response surface for which corresponding parameter values cannot be obtained under each theory[4]. However, as Figure 1 shows, except for the identical independence and exclusivity-*a* models, each task theory is characterized by a different set of isometric contours. It is therefore possible to distinguish between them by identifying experimental variables that selectively affect one or other of the underlying constructs. In other words, it is possible to identify the correct task theory if the correct process theory is known. However, as discussed above, there is considerable uncertainty concerning the identity of the correct process theory. For this reason, it is necessary to provisionally accept a candidate process theory and, in this context, to evaluate the set of task theories against the data. If this process theory is correct and one of the task theories is also correct, then the resulting combined model should provide a good fit to the data. On the other hand, if the process theory is incorrect, then given sufficient data, it is unlikely that any of the task theories will satisfactorily fit the data.

A process theory of the remember/know paradigm

Several researchers have proposed, at different times, that remember responses are based on conceptual processes and know responses are based on perceptual processes (e.g., Gardiner, 1988; Gregg & Gardiner, 1994; Rajaram, 1993, 1996; Yonelinas & Jacoby, 1995). This distinction is often characterized as a distinction between recollection and familiarity or perceptual fluency. Recollection is described as slow, intentional, attention demanding, dependent upon the similarity of conceptual processing at study and test, and involving the

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[4] This is not strictly true although it is nearly true. For each theory, except the process-pure variant, there exist values of *R* and *K* for which one or both parameters are undefined. Thus, in the independence model, *n* is undefined if $R = 1$; in the redundancy model, *a* is undefined if both $R = 0$ and $K = 0$; in the exclusivity-*n* model, *a* is undefined if $K = 1$; in the exclusivity-*a* model, *n* is undefined if $R = 1$; and in the fuzzy logic theory, *a* is undefined if $K = 1$ and *n* is undefined if $R = 1$. However, if the response surface is redefined as the intersection of the strict inequalities, $R > 0$, $K > 0$, $R + K < 1$, then each data point maps onto a unique pair of parameter values (and vice versa). In other words, the mapping defined by each model is bijective.

conscious retrieval of aspects of the study episode while familiarity is described as fast, automatic, relatively attention-free, dependent upon the similarity of perceptual processing at study and test, and leading to a subjective feeling of fluent processing that is attributed to past experience (Gardiner, 1988; Jacoby, 1983, 1991; Jacoby & Dallas, 1981; Mandler, 1980, 1991). This account will be adopted as the candidate process theory for the subsequent analyses.

Following the work of Jacoby and his colleagues, recollection is considered to be the principal process underlying direct memory tasks such as recognition and recall while familiarity is thought to underlie indirect memory tasks such as repetition priming in word stem completion. On this view, variables that selectively affect performance on direct memory tasks do so by affecting recollection, while variables that selectively affect performance on indirect memory tasks do so by affecting familiarity. Several variables have been shown to selectively affect direct memory tasks. Of these, some of the most extensively investigated are age, level of processing and divided attention at study. There is considerable evidence that age has a greater effect on performance on direct memory tasks than on priming in indirect memory tasks (for a recent review, see Light, Prull, La Voie & Healy, 2000). Although age has a non-negligible effect on indirect memory tasks, this can be interpreted as being due to contamination from recollective processes which may also have a small effect on these tasks. Similarly, there is good evidence that level of processing at study has a large effect on direct memory tasks but little or no effect on indirect memory tassks (e.g., Brooks, Gardiner, Kaminska & Beavis, 2001; Graf & Mandler 1984; Jacoby & Dallas, 1981). Division of attention at study also affects performance on direct memory tasks more than on indirect memory tasks (e.g., Mulligan, 1998; Wolters & Prinsen, 1997). In contrast to the number of variables that have been found to affect direct memory tasks, relatively fewer variables have been found to selectively affect indirect memory tasks. Of these, one of the most consistent has been a change in the modality (visual vs. auditory) of targets between study and test. Prior presentation of a target in the alternative modality has been found to reduce indirect memory effects by approximately half and to have little or no effect on direct memory tasks (e.g., Blum & Yonelinas, 2001; Kirsner, Milech & Standen, 1983; Roediger & Blaxton, 1987).

It is proposed that the parameters, a and n, in each task theory correspond to the processes underlying recollection and familiarity, respectively. If so, then manipulation of these variables will cause data to fall on the isometric contours of the correct task theory. IN particular, measures of R and K reflecting a change in either age, level of processing, or divided attention should fall on the isometric contours of constant n, while measures of R and K reflecting a change in stimulus modality should fall on the isometric contours of constant a. In order to test these predictions, studies were identified from the literature that investigated the effects of these variables on R and K responses. Although an attempt was made to identify as many relevant studies as possible, the final set is unlikely to be comprehensive. All of the selected studies employed a recognition memory task and the remember/know paradigm as originally described by Tulving (1985). Studies that used a modification of this paradigm which allows an additional response category for guesses (e.g., Gardiner & Conway, 1999) were not included.

Goodness of fit measure

Each study contributed one or more *comparisons* involving variation of one of the selected variables. A comparison is a set of p experimental conditions defined by variation of one of these variables. The goodness of fit of each task theory was evaluated by measuring the extent to which the data from each comparison conform to the appropriate isometric contour for this theory. If the experimental factor affects only parameter *a*, then these data should fall on an isometric contour of constant *n*. Similarly, if the factor affects only parameter *n*, then the data should fall on an isometric contour of constant *a*. Predicted values for each task theory were derived by fitting the data points using (p + 1) parameter estimates. These estimates correspond to *p* values of the parameter, *a* or *n*, that is assumed to vary in the comparison, and one value of the parameter that is assumed to be a constant. These estimates were derived by minimizing the *sum of squared error* (SSE) defined as,

$$\mathrm{SSE} = \sum_i^p \left(R_i - \hat{R}_i\right)^2 + \sum_i^p \left(K_i - \hat{K}_i\right)^2$$

where R_i and K_i are observed proportions of remember and know responses, respectively, under the *i*th condition of the comparison, and $\hat{R}_i$ and $\hat{K}_i$ are the corresponding predicted proportions. A useful transformation of the SSE is the *root mean squared error* (RMSD) here defined as,

$$\mathrm{RMSD} = \sqrt{\frac{\mathrm{SSE}}{(p-1)}}$$

The advantage of the RMSD measure is that it is on the same scale as the data and directly conveys information concerning the degree of model fit.

As shown in Figure 1, several task theories have equivalent isometric contours for one o other parameter. For comparisons that affect parameter *a*, the models fall into three groups. Group I consists of the independence, exclusivity-*a*, and fuzzy logic models. As shown by the solid lines in Figures 1a, 1e, and 1f, each these models predicts the same isometric contours of constant *n*. Group II consists of the process-pure and exclusivity-*n* models. As shown by the solid lines in Figures 1c and 1d, both of these models predict a second set of isometric contours of constant *n*. Finally, Group III consists solely of the redundancy model which, as shown by the solid lines in Figure 1b, predicts a third set of isometric contours of constant *n*. Comparisons of age, level of processing, and divided attention, which are assumed to affect only *a*, can distinguish between models belonging to different these groups but cannot distinguish between models within the same group.

Age

Eleven studies were identified that compared subjects of different ages (see Table 1). These studies comprised a total of 20 different comparisons that, in all but one case, involved a contrast between a group of relatively young subjects and a group of relatively older subjects (i.e., $p = 2$). The one exception was Experiment 2 of Parkin and Walter (1992) in which three different age groups were compared (i.e., $p = 3$). The proportions of remember and know responses for each of these 20 comparisons are plotted in Figure 2a. There is a general trend for remember and know responses to be negatively correlated across variation in age. There are, however, two notable exceptions to this trend. These are the results of Experiment 2a of Perfect, Williams and Anderton-Brown (1995), indicated by crosses in Figure 2a. These two results depart from all the other comparisons of age found in the literature and also fail to conform to any of the task theories under consideration. It is noteworthy that the authors of this study also remarked on the anomalous nature of these data but were unable to offer an explanation. For this reason, these results were excluded from further analysis[5].

Table 1
Effect of Age on Proportion of Remember (*R*) and Know (*K*) Responses

			Young		Old	
Study	Exp.	Condition	*R*	*K*	*R*	*K*
Fell (1992)		Shallow encoding	0.57	0.19	0.24	0.55
		Deep encoding	0.90	0.07	0.91	0.05
Friedman & Trott (2000)			0.50	0.22	0.43	0.23
Jacoby, Jennings & Hay (1996)			0.56	0.22	0.35	0.33
Java (1996)			0.25	0.11	0.14	0.09
Mark & Rugg (1998)			0.64	0.19	0.64	0.20
Maylor (1995)	1		0.62	0.21	0.50	0.24
Norman & Schacter (1977)	1	No explanation	0.53	0.26	0.51	0.22
		Explanation	0.54	0.25	0.55	0.21
Parkin & Walter (1992)	1		0.52	0.25	0.20	0.46
	2	Young/ Middle-aged	0.37	0.43	0.19	0.49
		Old			0.12	0.55
Perfect & Dasgupta (1997)	1	Words	0.81	0.15	0.58	0.20
		Nonwords	0.68	0.19	0.38	0.26
Perfect, Williams & Anderton-Brown (1995)	1		0.53	0.23	0.18	0.53
	2a	Shallow task	0.40	0.36	0.34	0.20
		Deep task	0.68	0.29	0.69	0.08
	2b		0.88	0.10	0.25	0.39
Schacter, Koutstaal, Johnson, Gross & Angell (1997)	1	1 repetition	0.83	0.06	0.70	0.08
		3 repetitions	0.77	0.08	0.68	0.08
	2		0.62	0.23	0.43	0.16

Each of the six task theories were fit to the data shown in Figure 2a. The Group I and Group III models are both consistent with the negative correlation of R and K responses across age although visual inspection of Figure 2a suggests that the data may conform more closely to the predictions of the Group I models. This impression is confirmed by the results of formal model evaluation. The goodness of fit of each group of models to each comparison is listed in the Appendix A and summarized in Figure 2b. This figure is a plot, called a *cp-plot*, of the cumulative proportions of the distribution of RMSD values corresponding to the goodness of fit of each group of models to each comparison. The relative fit of each group of models is indicated by the position of its corresponding cp-plot. The further it is shifted to the left, relative to other models, the better is its overall fit. Figure 2b shows that the cp-plot for Group I models is to the left of the cp-plots for both Group II and Group III models. The Group II models fit some comparisons to a similar degree as do the Group I models, but for other comparisons the fit is considerably poorer. This is reflected by the divergence of the cp-

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[5] Since none of the models under consideration predict these results their exclusion does not affect the conclusions drawn and perhaps provide a better indication of overall fit of each model.

plots for these two groups of models. The cp-plot of the redundancy model (Group III) is slightly different. Across all comparisons, this model fits the data as well as or better than the Group II models, but less well than the Group I models.

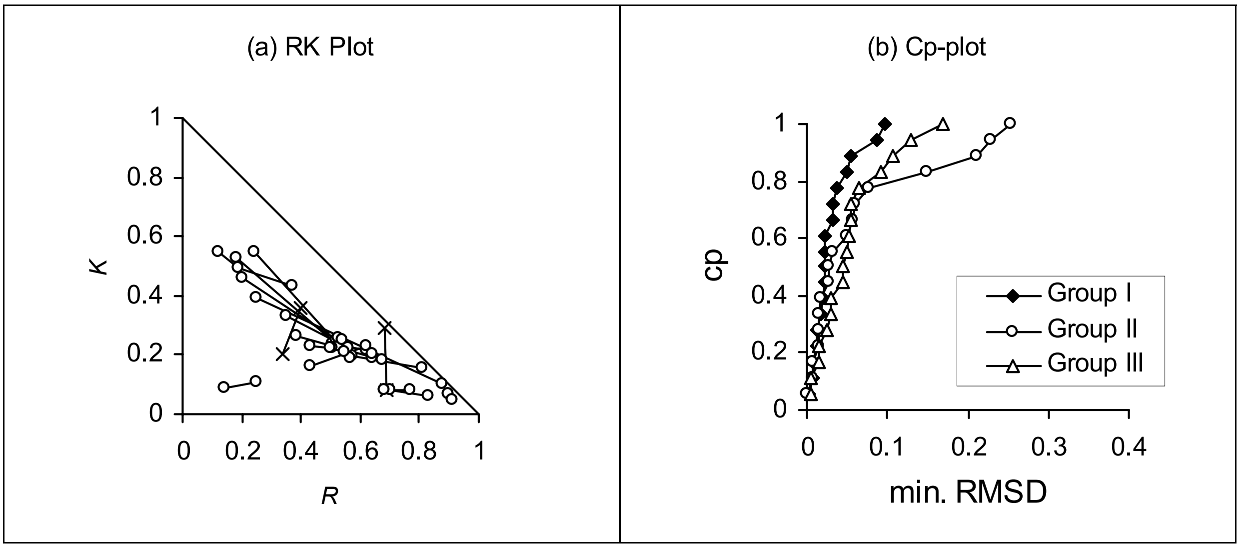

Figure 2. (a) The effect of variation in age on the proportion of remember and know responses. (b) Cumulative proportion plots of the fits of each group of models to comparisons based on variation in age (Group I = independence, exclusivity-*a*, fuzzy logic; Group II = process-pure, exclusivity-*n*; Group III = redundancy).

Level of processing

Eight studies were identified that examined the effect of variation in level of processing at study on remember and know responses (see Table 2). These studies contained a total of 14 different comparisons in which performance under a shallow encoding instruction, such as a letter or rhyme judgment task, was contrasted with performance under a deep encoding instruction, such as a semantic judgment task[6]. The results for these comparisons are given in the Appendix B and plotted in Figure 3a. Similar to the effect of age, remember and know responses are generally negatively correlated across changes in level of processing. The cp-plots of each group of models are shown in Figure 3b which reveals three principal effects. First, as found for comparisons of age, Group I models fit the data best. Second, across all comparisons the Group III (redundancy) model fits the data most poorly. Third, while the Group II models fit most comparisons almost as well as the Group I models, the fit to one comparison is considerably worse. This comparison concerns the results for older subjects reported by Fell (1992) and is indicated by the filled circles in Figures 3a and 3b. The principal reason for the failure of Group II models to account for this comparison is the fact that the two conditions in this comparison fall relatively close to the main diagonal in Figure 3a. The two Group II models, the process-pure and exclusivity-*n* models, predict that these conditions should fall on a horizontal line wholly within the RK response region. The best fit for such a line provides an extremely poor fit to these data.

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[6] The study by Macken & Hampson (1993) compared performance under incidental learning instructions with performance under intentional learning instructions. For present purposes, this manipulation is considered a variant of levels of processing.

Table 2
Effect of Level of Processing on Proportion of Remember (*R*) and Know (*K*) Responses

			Shallow		Deep	
Study	Exp.	Condition	*R*	*K*	*R*	*K*
Fell (1992)		Young subjects	0.57	0.19	0.90	0.07
		Old subjects	0.24	0.55	0.91	0.05
Gardiner (1988)	1		0.47	0.16	0.67	0.18
Gregg & Gardiner (1994)	1	Auditory	0.37	0.29	0.62	0.24
		Visual	0.25	0.38	0.59	0.30
Java, Gregg & Gardiner (1997)	2		0.50	0.22	0.71	0.10
Khoe, Kroll, Yonelinas, Dobbins & Knight (2000)	1	Yes-No	0.16	0.29	0.26	0.34
		Forced Choice	0.15	0.48	0.31	0.43
Macken & Hampson (1993)		1 repetition	0.16	0.26	0.31	0.23
		3 repetitions	0.23	0.24	0.38	0.27
		6 repetitions	0.23	0.27	0.36	0.27
Perfect, Williams & Anderton-Brown (1995)	2a	Young subjects	0.40	0.36	0.68	0.29
		Old subjects	0.34	0.20	0.69	0.08
Rajaram (1993)	1		0.32	0.30	0.66	0.20

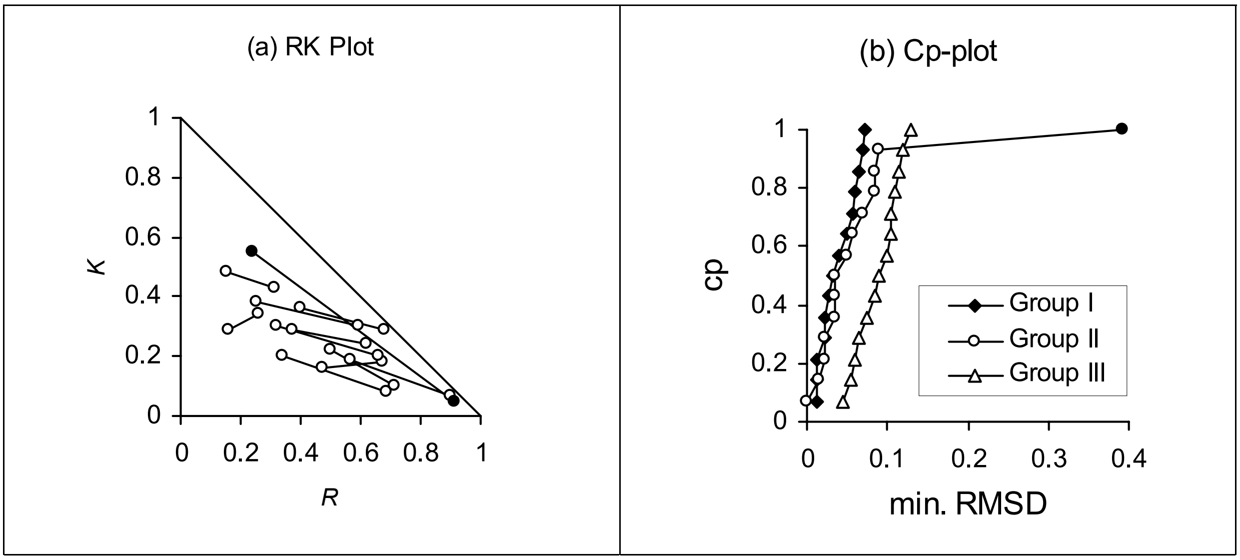

Figure 3. (a) The effect of variation in level of processing on the proportion of remember and know responses. (b) Cumulative proportion plots of the fits of each group of models to comparisons based on variation in level of processing (Group I = independence, exclusivity-*a*, fuzzy logic; Group II = process-pure, exclusivity-*n*; Group III = redundancy).

Divided attention

Three studies were identified that examined the effect of divided attention at study on remember and know responses (see Table 3). These comprised three different comparisons in which performance under a focused attention condition is contrasted with performance under one or more divided attention conditions. The results for these three comparisons are listed in the Appendix C and plotted in Figure 4a. Although there are relatively few comparisons, the results are consistent in showing that divided attention at study has a larger effect on remember responses than on know responses. While this is broadly consistent with the predictions of the Group II models, because of the location of these data within the RK response surface, the results are also reasonably consistent with the predictions of the Group I models. That is, the data happen to occupy a region of the response surface in which the isometric contours of Group I models are relatively flat. These observations are confirmed by formal model evaluation. The cp-plots of each group of models are shown in Figure 4b. Although the Group II models fit these data the best, the Group I models appear to provide only a slightly worse fit. The redundancy model provides the poorest fit to these data.

Table 3
Effect of Divided Attention on Proportion of Remember (*R*) and Know (*K*) Responses

			Focused		Divided	
Study	Exp.	Condition	*R*	*K*	*R*	*K*
Gardiner & Parkin (1990)	1	Divided 1	0.50	0.20	0.38	0.20
		Divided 2			0.27	0.22
Mangels, Picton, & Craik (2001)		Easy divided	0.63	0.24	0.53	0.25
		Hard divided			0.17	0.34
Parkin, Gardiner & Rosser (1995)	1		0.43	0.22	0.30	0.23

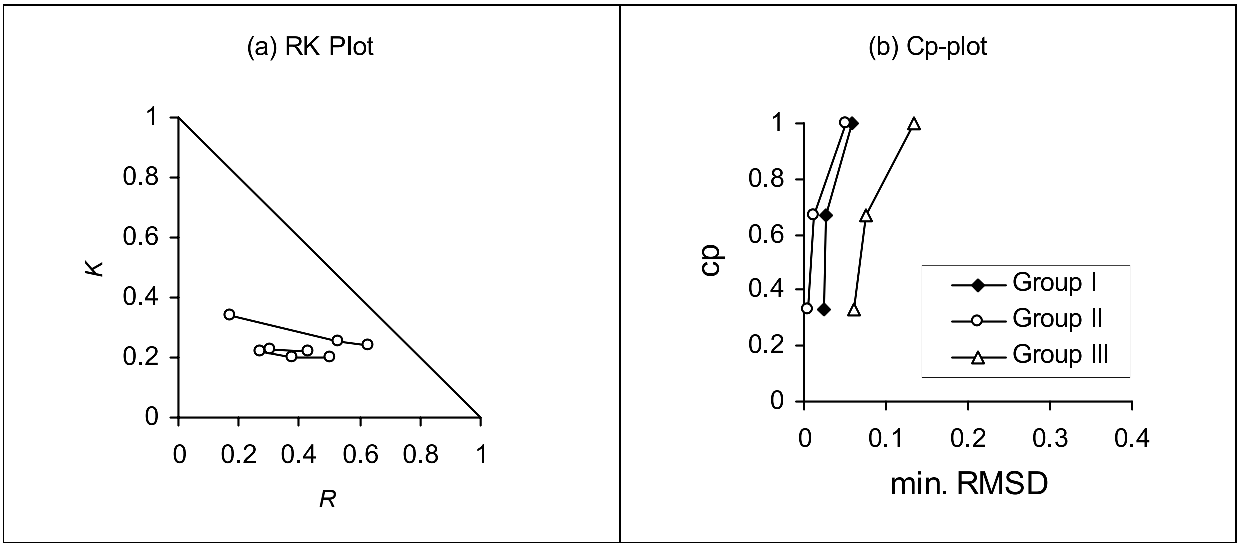

Figure 4. (a) The effect of variation in divided attention on the proportion of remember and know responses. (b) Cumulative proportion plots of the fits of group of models to comparisons based on variation in divided (Group I = independence, exclusivity-*a*, fuzzy logic; Group II = process-pure, exclusivity-*n*; Group III = redundancy).

Combined analysis

Variation in age, level of processing and divided attention are all assumed to affect R and K responses through the single process of recollection. Therefore, a good estimate of the relative goodness of fit of each group of models could be obtained by combining the results from each set of comparisons. Figure 5 presents the cp-plots of each group of models for all comparisons involving variation in these three variables. This shows that the Group I models provide the best fits to the data, the Group II models provide relatively good fits to most of the data but provide particularly poor fits to a few crucial comparisons. The comparisons most at variance with the predictions of the Group II models (with minimum RMSD values greater than 0.1) are those found by Fell (1992) for older subjects, Fell (1992) for the shallow encoding task, Perfect et al. (1995; Experiments 1 and 2b), and Parkin & Walter (1992; Experiment 1).

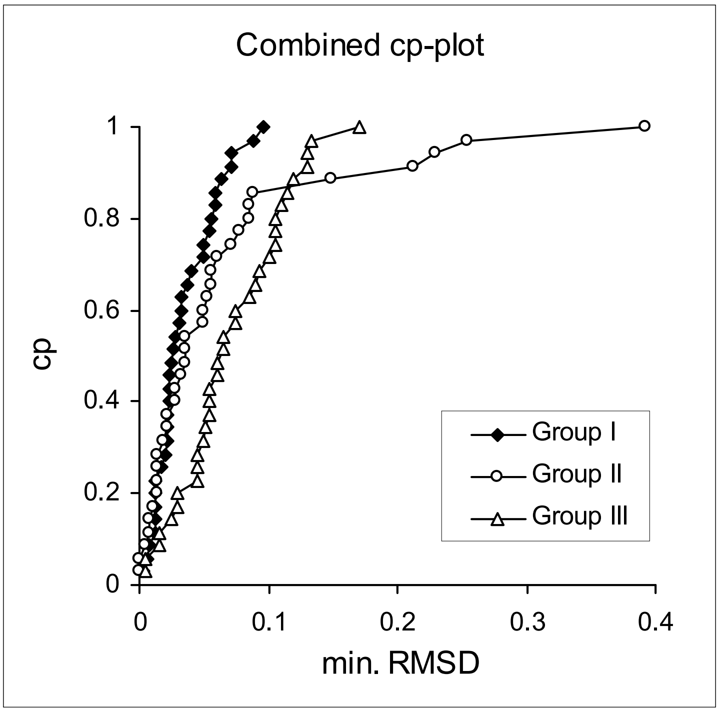

Figure 5. Cumulative proportion plots of the fits of each group of models to comparisons based on variation in age, level of processing, and divided attention (Group I = independence, exclusivity-*a*, fuzzy logic; Group II = process-pure, exclusivity-*n*; Group III = redundancy).

Stimulus modality

Since comparisons of stimulus modality are assumed to vary only parameter *n*, the six models can be classified into three further groups – Groups IV, V, and VI. Group IV is comprised of the exclusivity-*n* and fuzzy logic models. As shown by the dashed lines in Figures 1d and 1f, these models predict equivalent isometric contours of constant *a*. Group V is made up of the independence, process-pure, and exclusivity-*a* models (dashed lines in Figures 1a, 1c, and 1e), while Group VI consists solely of the redundancy model (dashed lines in Figure 1b).

Three studies were identified that examined the effect on remember and know responses of changing stimulus modality (visual or auditory) between study and test (see Table 4). They comprised a total of six different comparisons in which performance under a same modality condition is contrasted with performance under a different modality condition. The results for each of the six comparisons are listed in the Appendix D and plotted in Figure 6a. In contrast to the effects of age, levels of processing, and divided attention, variation in stimulus modality does not appear to demonstrate a consistent effect. A number of relationships between R and K responses can be observed; a selective effect on *K*, a selective effect on *R*, and a negative correlation between *R* and *K*. This observation is reinforced by formal model fitting. The cp-plots for each group of models is shown in Figure 6b. Although there are relatively few data points, no one group of models appears to fit these data better than the others.

Table 4
Effect of Stimulus Modality on Proportion of Remember (*R*) and Know (*K*) Responses.

			Same modality		Different modality	
Study	Exp.	Condition	*R*	*K*	*R*	*K*
Gregg & Gardiner (1994)	1	Deep encoding	0.62	0.24	0.59	0.30
	1	Shallow encoding	0.37	0.29	0.25	0.38
	2	Intentional/slow rate	0.69	0.12	0.66	0.17
	2	Incidental/fast rate	0.10	0.27	0.11	0.52
Rajaram (1993)	1		0.49	0.25	0.49	0.25
Wagner, Gabrieli & Verfaellie (1997)	4		0.26	0.27	0.48	0.24

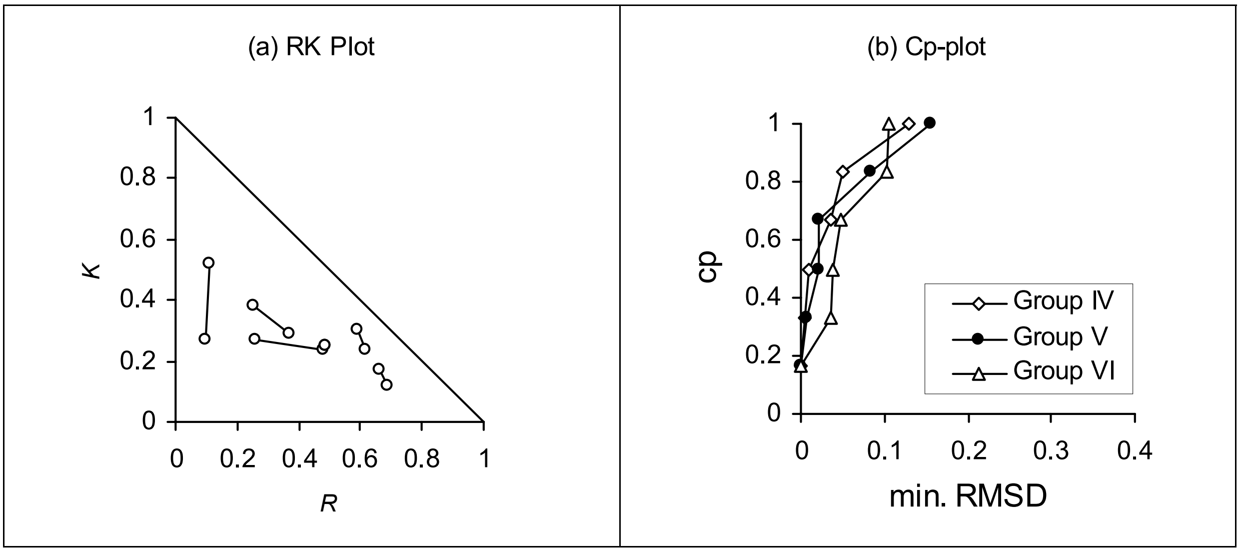

Figure 6. (a) The effect of variation in stimulus modality on the proportion of remember and know responses. (b) Cumulative proportion plots of the fits of each group of models to comparisons based on variation in stimulus modality (Group IV = exclusivity-*n*, fuzzy logic; Group V = independence, exclusivity-*a*, process-pure; Group VI = redundancy;).

Some measurement issues

The present analyses reveal that variation in age, level of processing, and divided attention are best accounted by Group I models, consisting of the independence, exclusivity-*a*, and fuzzy logic models. This conclusion is based solely on the relatively smaller RMSD values associated with this group of models. This, in turn, assumes that none of the six models under review enjoys any *a priori* advantage over the remaining models in its ability to fit data of this sort. There are two issues that could affect model comparison. The first concerns the effect of averaging across subjects, the second concerns differences in model complexity or flexibility. These issues are discussed in turn.

The present analysis is based the mean proportions of R and K responses averaged over subjects. However, in some cases, averaging over subjects can lead to small but systematic deviations in the observed means (Busemeyer & Jones, 1983; Myung & Kim, 2000). Generally, it may be assumed that subjects differ on the values of the underlying parameters, *a* and *n* (Massaro, Cohen, Campbell, & Rodriguez, 2001). If the observed measures are linear combinations of these parameters then the average across subjects is well-estimated by applying this linear combination to the average of the individual parameter values. Of the six task theories under consideration, only the process-pure model is linear in this sense. Therefore, if each subject conforms to this model, the average will also conform to the model. In contrast, if the observed measures are nonlinear functions of the parameters, as in the remaining models, then even if each subject conforms to the model in question, this model will not describe the average across subjects. In other words, while the averaged data will no longer on the isometric contour of the correct model. Specifically, these data will tend towards the isometric contour of the linear, or process-pure, model. As a result, the process-pure model enjoys an *a priori* advantage over the other models in this respect[7].

The second issue concerns model complexity or flexibility. This has been defined by Myung and Pitt (1997) as, “the flexibility inherent in a model that enables it to fit diverse patterns of data” (p. 80). If models differ in complexity then their respective minimum RMSD values need to be interpreted with caution. Specifically, a model may fit the data well simply as a consequence of its inherent capacity to fit almost any data, no matter what its form. Recently, Dunn (2000) has suggested that model complexity can be evaluated by calculating the average fit of a model to arbitrary or random data. If a model has the capacity to fit any or most patterns of data then its mean minimum RMSD value for arbitrary data should be small. This can be calculated by fitting the each model to a random sample of all possible pairs of points on the *RK* response surface. Usefully, this calculation also provides a means of evaluating the magnitudes of the obtained RMSD values. The mean minimum RMSD of a model provides a upper limit to a satisfactory fit. If the observed minimum RMSD value of a model is similar to its mean minimum RMSD, then the model fits these data no better than data selected at random. In other words, it does not fit the data at all.

Since each of the six unconstrained task theories shown in Figure 1 accounts for all possible combinations of R and K, none is inherently more complex than the other. Differences arise only in the special case under consideration in which a comparison of p conditions, consisting of $2p$ points, is fit by a model consisting of $(p+1)$ parameters. Under these circumstances, the set of models differ in their functional form. As discussed by Myung and Pitt (1997), model complexity depends on three factors; the number of parameters, the extent of parameter space, and the form of the function that maps parameters onto outcomes. As all the models under consideration have the same number of parameters, and each parameter has the same extent (that is, from zero to one), differences in model complexity are entirely due to differences in their functional form.

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[7] The same effect applies to estimates of recollection and familiarity derived from the Process Dissociation Procedure if these are based on averaged data. To avoid this, it is necessary to calculate parameter estimates for each subject individually and then to average these.

Since functional form dictates complexity, there is not one but two complexity measures for each model, depending upon which parameter, either *a* or *n*, is constrained to be a constant. Inspection of Figure 1 reveals that the isometric contours of each model correspond to one of four types. These are, (a) contours parallel to one or other axis as found in Group II and Group V models, (b) contours parallel to the negative diagonal as found in the redundancy model for constant-*n*, (c) contours radiating from the origin as found in the redundancy model for constant-*a*, and (d) contours radiating from one of the extreme points, excluding the origin, as found in Group I and Group IV models. Each of these types is associated with a different value for the mean minimum RMSD. Estimates for these values were obtained by selecting a pair of points on the *RK* response surface at random, fitting a model of each type to these points, and calculating the resulting minimum RMSD.

Table 5
Mean Minimum RMSD of the Fit of each Model to Arbitrary Data

	Constant *n*		Constant *a*	
Model	Group	Mean min.RMSD	Group	Mean min.RMSD
Independence/ Exclusivity-*a*	I	0.126	V	0.189
Exclusivity-*n*	II	0.189	IV	0.126
Process-pure	II	0.189	V	0.189
Redundancy	III	0.136	VI	0.187
Fuzzy Logic	I	0.126	IV	0.126

Table 5 presents the mean minimum RMSD values based on fitting each model to 10^7 random two-point comparisons. Relatively low values indicate greater complexity or flexibility for the model in question. Concerning contours of constant *n*, Group I models (independence, exclusivity-*a*, fuzzy logic) are the most flexible in this sense. That is, a pair of randomly selected points on the *RK* response surface is, on average, closer to an isometric contour of this group of models than it is to a contour of any other group of models. Group II models (process-pure, exclusivity-*n*) are the least flexible in this sense, while the Group III model (redundancy) is intermediate. For comparisons of constant *a*, Group IV models (exclusivity-*n*, fuzzy logic) are the most flexible while Group V models (independence, exclusivity-*a*, process-pure) and the Group VI model (redundancy) are the least flexible. Therefore, for comparisons of age, level of processing, and divided attention, the independence, exclusivity-*a*, and fuzzy logic models and, to a lesser extent, the redundancy model enjoy an *a priori* advantage relative to the process-pure and exclusivity-*n* models. Similarly, for comparisons of stimulus modality, the exclusivity-*n* and fuzzy logic models enjoy an advantage relative to the remaining models.

The analysis of measurement issues based on averaging and model complexity indicates that the set of models are not equally comparable. Unfortunately, although it is possible to observe that a model may have an *a priori* advantage or disadvantage relative to other models, it is not possible to quantify these effects. All that can be done at this stage is to take account them qualitatively when interpreting the fit of each model to the data.

GENERAL DISCUSSION

The present study yields two main sets of results. The first set concerns the effects of age, level of processing, and divided attention on remember and know responses. It is assumed that the effects of these variables on remember and know responses are mediated solely by the process of recollection. Therefore, comparisons involving these variables should fall on the isometric contours of constant *n* of the correct task theory. As shown in Figures 2a, 3a, and 4a, although there appears to be considerable variability in the averaged data from all the relevant studies, R and K responses tended to be negatively correlated across changes in these variables. This pattern is most consistent with the models in Group I, the independence, exclusivity-*a*, and fuzzy logic models. And this is confirmed by formal model fitting. As shown in Figure 5, the Group I models fit the data from these comparisons consistently better than do either the Group II or Group III models.

If the process theory, that recollection is selectively affected by age, level of processing, and divided attention, is correct, then the data support the view that the most viable task theory is either the independence/exclusivity-*a* model or the fuzzy logic model. However, several qualifications must be made. First, the present analysis has provided only a measure of the *relative* goodness of fit of these models. Although the models from Group I fit the data better than the remaining models, it is unclear whether they provide a genuinely satisfactory or “good” fit. Although the general trend of the data conforms to the predictions of these models, there is much unexplained variability. While it is likely that much of this variability is due to error of measurement, some of it may also reflect systematic deviations. Second, although the Group II models perform less well than those in Group I, much of this disparity is due to the results of just five comparisons. The results from two other comparisons (Perfect et al., 1995; Experiment 2b) were not included in the present analysis because they appeared to be anomalous. It is possible that these five comparisons which are uniquely inconsistent with the Group II models, could also be anomalous in some way. Further research, aimed at inducing both a large effect size and increased precision of measurement, is needed to clarify these issues.

The present conclusion is contingent on the candidate process theory being correct. If this theory is incorrect, there is no reason to expect R and K responses to fall on the isometric contours of the correct task theory. In this situation no theory would be expected to correspond to the data better than another. Under these circumstances, the difference between the Group I and Group II models would reflect the greater flexibility of the former. However, even if this were true, differences in model flexibility cannot account for the failure of the Group II models to account for the five critical comparisons. If real, these results count significantly against these models. In addition, differences in flexibility cannot account for the relatively poor fit of the redundancy model. Across nearly all comparisons of constant *n*, this model fits the data less well than any of the other models. But, as Table 5 shows, this model is more flexible than the Group II models and only slightly less flexible than the Group I models. Taken together, this suggests that the data depart systematically from the predictions of this model.

Across changes of age, level of processing, and divided attention, the data are most consistent with the independence/exclusivity-*a* and fuzzy logic models. However, further research is required in order to resolve whether the candidate process theory is indeed correct. Other variables, such as memory disorder, study duration, and response deadline[8], have also

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[8] A recent study by Gardiner, Ramponi & Richardson-Klavehn (1999) found that remember and know responses are positively associated across changes in response deadline. On the face of it, this result is inconsistent with all of the task theories under consideration, but because it employed the remember/know/guess procedure its relevance is uncertain.

been identified as selectively affecting a recollection (Kelley & Jacoby, 2000). Therefore, if the candidate process theory is correct, Group I models should also provide the best fit to comparisons involving these variables.

The second set of results concerns the effect of stimulus modality on remember and know responses. It was assumed that the effect of this variable on R and K responses is mediated by perceptual fluency or familiarity and hence that the relevant comparisons should fall on the isometric contours of constant *a* of the correct task theory. The results plotted in Figure 6a show a considerable level of variability with none of the models able to fit the data better than the others. This suggests one of the following conclusions. First, there may be insufficient data to adjudicate between the models. With only six comparisons, it is clear that further investigation of the effect of stimulus modality on R and K responses is required. The second conclusion is that the candidate process model is incorrect. In particular, that the process characterized by the parameter *n* is not selectively affected by a change in stimulus modality. There is some independent evidence for this view.

Recently, Wagner and his colleagues have suggested that recognition familiarity is dissociable from perceptual fluency (Wagner, Gabrieli & Verfaellie, 1997; Wagner & Gabrieli, 1998; Wagner, Stebbins, Masciari, Fleischman & Gabrieli, 1998). In a review of several studies, Wagner and Gabrieli (1998) have presented evidence that recognition familiarity, as indexed by the process dissociation procedure, is affected by different variables to those that affect perceptual fluency, as indexed by repetition priming in an indirect memory task. If this view is correct, and the familiarity process underlying R and K responses is the same as recognition familiarity, then it need not be affected by changes in stimulus modality. Consequently, no group of task theories should fit these data better than any other group. This is consistent with the results of the present study. If recognition familiarity is not the same as perceptual fluency, then this component of the candidate process theory needs to be revised. Specifically, consideration needs to be given to the kinds of variables that can be shown to selectively influence recognition familiarity as opposed to perceptual priming. In their review of the evidence, Wagner and Gabrieli (1998) have suggested that changes in size congruency between study and test appear to affect recognition familiarity, but appear to have little or no effect on repetition priming. The effect of this variable on remember and know responses has been investigated by both Rajaram (1996) and Yonelinas and Jacoby (1995). Although these studies yield only two comparisons, it is instructive that they are sufficient to differentiate the three groups of models. The results indicate that the Group IV models (fuzzy logic and exclusivity-*n*) provide better fits than do either the Group V or Group VI models.

The present evidence supports the view that the independence/exclusivity-*a* model and the fuzzy logic model are most consistent with the effects of age, level of processing, and divided attention on R and K responses, under the assumption that these variables selectively affect the first or recollection process. Since these three models make identical predictions concerning the effects of these variables, they can only be differentiated by comparisons involving variables presumed to selectively affect the second or familiarity process. At the present time there is both insufficient data and certainty concerning the identity of the relevant variables to reach a definitive conclusion. However, the present analysis does suggest that of the four exclusivity-like models, process-pure, exclusivity-*n*, exclusivity-*a*, and fuzzy logic, only the exclusivity-*a* and fuzzy logic models are strongly supported by the data. Bearing in mind that the exclusivity-*a* model is formally identical to the independence model, this means that the fuzzy logic model is the only exclusivity variant for which there is at present strong evidence.

The conclusion that there is more support for fuzzy logic than for the process-pure variant of exclusivity rests upon the assumptions of the present approach. This is predicated on the view that the nature of the relationships between remember and know responses and hypothetical underlying processes is an empirical question. Jacoby and his coworkers have argued for a similar point of view. In their discussion of this issue, Jacoby et al. (1997) suggest that one of the reasons for favoring the independence model is that adoption of this task theory renders the results of a number of experiments more interpretable or meaningful. That is, by adopting the independence model, the data are found to conform more closely to a process theory based on the distinction between recollection and familiarity. In contrast to this approach, several researchers have argued that the question of which task theory is correct can be resolved on *a priori* grounds (e.g., Gardiner 2000; Gardiner, Ramponi & Richardson-Klavehn, 1998; Rajaram & Roediger, 1997). On this view, the process-pure exclusivity model is necessarily correct by virtue of the nature of the research question.

The research question of interest to Gardiner and his coworkers and Rajaram and her coworkers concerns explication of the states of consciousness that underlie remember and know responses. Accordingly, Gardiner, Ramponi & Richardson-Klavehn (1998) propose that “remember and know responses measure *states* of awareness” (p. 10), to be contrasted with recollection and familiarity which “are conceived as independent processes, not as states of awareness” (p. 11). Confusion between the concepts of a state and a process has been called a “category mistake” by Gardiner (2000). Similarly, Rajaram and Roediger (1997) state that they “are interested in a first-person account of subjects’ states of awareness, and so leave it to them to determine this quality for each item” (p. 217). Consequently, remember and know responses are interpreted as reflecting their corresponding states of awareness, by definition.

That remember and know responses reflect different states of subjective awareness is, in one sense, trivially true. It is trivially true that a different state of awareness must underlie almost any response that can elicited from a person. In this sense, a state of awareness is nothing more than the mental configuration that leads a subject to produce the response in question. Therefore, investigation of such states is necessarily isomorphic to the investigation of the responses they elicit. Why then should the states of awareness underlying remember and know responses, as opposed to a potentially infinite number of other responses, be singled out for programmatic study? In reply, Gardiner et al (1998) suggest the following chain of reasoning; “(a) there are reasons to suppose that there are separate episodic and semantic systems in the brain; (b) these systems appear to be associated with two different kinds of consciousness; (c) awareness reflecting these two different kinds of consciousness can be measured by remember and know responses; and (d) it is therefore possible to check, using these measures, whether remembering and knowing behave in the kind of way we would expect, on the basis of all other evidence.” (pp. 10-11). In other words, remember and know responses are of interest because they index states of consciousness that are associated with different underlying memory systems. On this view, the states of consciousness are not of interest in and of themselves but only insofar as they reflect basic memory systems or processes. If we suppose that states of awareness are caused by such mental processes (Crick, 1995; Gazzaniga, 1998), then it is clear that research should be concerned with an account of the nature of these processes, how each is affected by different experimental variables, and how they determine a set of overt responses and the corresponding states of awareness that each of these responses represents.

Rajaram and Roediger (1997) wish to contrast a first-person account of mental phenomena with a third-person account. A first-person account concerns descriptions of the states of consciousness underlying different response alternatives. A third-person account concerns descriptions of the objective properties of memory processes underpinning these states. It is important to understand that these accounts, and associated terminology, do not represent alternative and competing models, but are simply different ways of talking about the same thing. This idea can be illustrated with reference to the fuzzy logic model presented earlier. According to this model, the probabilities of remember and know responses depend upon a sequence of three underlying processes - feature evaluation, feature integration, and decision making. In the context of the studies that examine the effects of different experimental variables on R and K responses, the probability of each of kind of response depends ultimately on the feature evaluation stage through changes in the parameters, a and n. Although presented as an account of response probability, it is important to realize that this model can also be interpreted as an account of the corresponding states of consciousness. On this view, the probability of a remember response is equivalent to the probability of being in a state of autonoetic awareness and the probability of a know response is equivalent to the probability of being in a state of noetic awareness. However the nature of these states are determined by the different sources of information on which each depends. As a result, autonoetic consciousness is dominated by information concerning related personal experiences, intra- and extra-list associations, and imagery, while noetic consciousness is dominated by strong feelings of familiarity (Gardiner et al., 1998). The point is that the appropriate first-person account, expressed in terms of states of awareness, both arises from and is consistent with a corresponding third-person account, expressed in terms of hypothetical memory processes.

Conclusion

Despite extensive research involving the remember/know paradigm, there is considerable uncertainty concerning the nature of the processes underlying remember and know responses and how each of these processes determines the two kinds of response. The present study has outlined and implemented a strategy for resolving this uncertainty. The results indicate that across comparisons involving age, level of processing and divided attention, the existing data are more consistent with the independence and fuzzy logic models than with the process-pure exclusivity and redundancy models. However, across comparisons involving a change in stimulus modality, the data fail to adjudicate between the different accounts. While further research is needed to clarify these indications, the present strategy offers a means by which progress in the evaluation of dual-process models of the remember/know paradigm can be achieved.

REFERENCES

References marked with an asterisk indicate studies included in the data analysis.

Blum, D. & Yonelinas, A. P. (2001). Transfer across modality in perceptual implicit memory. *Psychonomic Bulletin & Review,* **8**, 147-154.

Brooks, B. M., Gardiner, J. M., Kaminska, Z., & Beavis, Z. (2001). Implicit versus explicit retrieval of surnames of famous people: Dissociative effects of levels of processing and age. *Journal of Memory and Language,* **44**, 118-130.

Busemeyer, J. R. & Jones, L. E. (1983). Analysis of multiplicative combination rules when the causal variables are measured with error. *Psychological Bulletin,* **93**, 549-562.

Crick, F. (1995). *The astonishing hypothesis: The scientific search for the soul.* New York: Simon & Schuster.

Donaldson, W. (1996). The role of decision processes in remembering and knowing. *Memory & Cognition,* **24**, 523-533.

Dunn, J. C. (2000). Model complexity: The fit to random data reconsidered. *Psychological Research,* **63**, 174-182.

Dunn, J. C. & Kirsner, K. (1989). Implicit memory: Task or process? In, S. Lewandowsky, J. C. Dunn & K. Kirsner (Eds.), *Implicit memory: Theoretical issues* (pp. 17-31). Hillsdale, NJ: Erlbaum.

* Fell, M. (1992). Encoding, retrieval and age effects on recollective experience. *The Irish Journal of Psychology,* **13**, 62-78.

* Friedman, D. & Trott, C. (2000). An event-related potential study of encoding in young and older adults. *Neuropsychologia,* **38**, 542-557.

* Gardiner, J. M. (1988). Functional aspects of recollective experience. *Memory & Cognition,* **16**, 309-313.

Gardiner, J. M. (2000). On the objectivity of subjective experiences of autonoetic and noetic consciousness. In E. Tulving (Ed.), *Memory, consciousness, and the brain: The Tallinn Conference* (pp. 159-172). Philadelphia, PA: Psychology Press.

Gardiner, J. M. & Conway, M. A. (1999). Levels of awareness and varieties of experience. In, B. M. Challis & B. M. Velichovsky (Eds.), *Stratification in cognition and consciousness* (pp. 237-254). Amsterdam: John Benjamins.

* Gardiner, J. M., & Parkin, A. J. (1990). Attention and recollective experience in recognition memory. *Memory & Cognition,* **18**, 579-583.

Gardiner, J. M., Ramponi, C., & Richardson-Klavehn, R. (1998). Experiences of remembering, knowing, and guessing. *Consciousness and Cognition,* **7**, 1-26.

Gardiner, J. M., Ramponi, C., & Richardson-Klavehn, R. (1999). Response deadline and subjective awareness in recognition memory. *Consciousness and Cognition,* **8**, 484-496.

Gardiner, J. M. & Richardson-Klavehn, R. (2000). Remembering and knowing. In, E. Tulving & F. I. M. Craik (Eds.), *The Oxford handbook of memory* (pp. 229-244). Oxford, UK: Oxford University Press.

Gazzaniga, M. (1998). *The mind's past*. Berkeley, CA: University of California Press.

Graf, P. & Mandler, G. (1984). Activation makes words more accessible, but not necessarily more retrievable. *Journal of Verbal Learning and Verbal Behavior,* **23**, 553-568.

* Gregg, V. H. & Gardiner, J. H. (1994). Recognition memory and awareness: A large effect of study-test modalities on "know" responses following a highly perceptual orienting task. *European Journal Cognitive Psychology*, **6**, 131-147.

Hirshman, E. (1998). On the utility of the signal detection model of the remember-know paradigm. *Consciousness and Cognition, 7*, 103-107.

Inoue, C. & Bellezza, F. S. (1998). The detection model of recognition using know and remember judgments. *Memory & Cognition,* **26***,* 299-308.

Jacoby, L. L. (1983). Remembering the data: Analyzing interactive processes in reading. *Journal of Verbal Learning and Verbal Behavior,* **22**, 485-508.

Jacoby, L. L. (1991). A process dissociation framework: Separating automatic from intentional uses of memory. *Journal of Memory and Language,* **30**, 513-541.

Jacoby, L. L. & Dallas, M. (1981). On the relationship between autobiographical memory and perceptual learning. *Journal of Experimental Psychology: General,* **110**, 306-340.

* Jacoby, L. L., Jennings, J. M., & Hay, J. F. (1996). Dissociating automatic and consciously controlled processes: Implications for diagnosis and rehabilitation of memory deficits. In, D. J. Herrmann, C. McEvoy, C. Hertzof, P. Hertel, & M. K. Johnson (Eds.), *Basic and applied memory research: Theory in context* (Vol. 1, pp. 161-193). Mahwah, NJ: Erlbaum.

Jacoby, L. L., Yonelinas, A. P., & Jennings, J. M. (1997). The relation between conscious and unconscious (automatic) influences: A declaration of independence. In, J. D. Cohen & J. W. Schooler (Eds.), *Scientific approaches to consciousness* (pp.13-47). Mahwah, NJ: Erlbaum.

* Java, R. I. (1996). Effects of age on state of awareness following implicit and explicit word association tasks. *Psychology and Aging,* **11***,* 108-111.

* Java, R. I., Gregg, V. H., & Gardiner, J. M. (1997). What do people actually remember (and know) in "remember/know" experiments? *European Journal of Cognitive Psychology, 9,* 187-197.

Jones, G. V. (1987). Independence and exclusivity among psychological processes: Implications for the structure of recall. *Psychological Review,* **94***,* 229-235.

Kelley, C. M. & Jacoby, L. L. (2000). Recollection and familiarity. In, E. Tulving & F. I. M. Craik (Eds.), *The Oxford handbook of memory* (pp. 215-228). Oxford, UK: Oxford University Press.

* Khoe, W., Kroll, N. E. A., Yonelinas, A. P., Dobbins, I. A., & Knight, R. T. (2000). The contribution of recollection and familiarity to yes-no and forced-choice recognition tests in healthy subjects and amnesics. *Neuropsychologia,* **38**, 1333-1341.

Kirsner, K., Milech, D., & Standen, P. (1983). Common and modality-specific processes in the mental lexicon. *Memory & Cognition,* **11**, 621-630.

Knowlton, B. (1998). The relationship between remembering and knowing: A cognitive neuroscience perspective. *Acta Psychologica,* **98***,* 253-265.

Knowlton, B. J. & Squire, L. R. (1995). Remembering and knowing: Two different expressions of declarative memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **21**, 699-710.

Light, L. L., Prull, M. W., La Voie, D. J., & Healy, M. R. (2000). Dual-process theories of memory in old age. In, T. J. Perfect & E. A. Maylor (Eds.), *Models of cognitive aging* (pp. 238-300). Oxford: Oxford University Press.

Luce, R. D. (1959). *Individual choice behavior*. New York: Wiley.

* Macken, W. J. & Hampson, P. (1993). Integration, elaboration and recollective experience. *The Irish Journal of Psychology*, **14**, 270-285.

Mandler, G. (1980). Recognizing: The judgment of previous occurrence. *Psychological Review,* **87**, 252-271.

Mandler, G. (1991). Your face looks familiar but I can't remember your name: A review of dual process theory. In, W. E. Hockley, S. Lewandowsky (Eds.), *Relating theory and data: Essays on human memory in honor of Bennett B. Murdock* (pp. 207-225). Hillsdale, NJ: Erlbaum.

* Mangels, J. A., Picton, T. W., & Craik, F. I. M. (2001). Attention and successful episodic encoding: An event-related potential study. *Cognitive Brain Research,* **11**, 77-95.

* Mark, R. E. & Rugg, M. D. (1998). Age effects on brain activity associated with episodic memory retrieval: An electrophysiological study. *Brain,* **121**, 861-873.

Massaro, D. W. (1998). *Perceiving talking faces*. Cambridge, MA: MIT Press.

Massaro, D. W. & Cohen, M. M. (2000). Fuzzy logical model of emotion perception: Comments on "The perception of emotions by ear and by eye" by de Gelder & Vroomen. *Cognition and Emotion,* **14**, 313-320.

Massaro, D. W., Cohen, M. M., Campbell, C. S., & Rodriguez, T. (2001). Bayes factor of model selection validates FLMP. *Psychonomic Bulletin & Review,* **8**, 1-17.

Massaro, D. W. & Friedman, D. (1990). Models of integration given multiple sources of information. *Psychological Review,* **97**, 225-252.

* Maylor, E. A. (1995). Remembering versus knowing television theme tunes in middle-aged and elderly adults. *British Journal of Psychology,* **86**, 21-25.

Mulligan, N. W. (1998). The role of attention during encoding in implicit and explicit memory. *Journal of Experimental Psychology: Learning, Memory and Cognition,* **24**, 27-47.

Myung, I. J. & Kim, C. (2000). Toward an explanation of the power law artifact: Insights from response surface analysis. *Memory & Cognition,* **28**, 832-840.

Myung, I. J. & Pitt, M. A. (1997). Applying Occam's razor in modeling cognition: A Bayesian approach. *Psychonomic Bulletin & Review,* **4**, 79-95.

* Norman, K. A. & Schacter, D. L. (1997). False recognition in younger and older adults: Exploring the characteristics of illusory memories. *Memory & Cognition,* **25**, 838-848.

* Parkin, A. J. & Walter, B. M. (1992). Recollective experience, normal aging and frontal dysfunction. *Psychology and Aging,* **7**, 290-298.

* Parkin, A. J., Gardiner, J. M., & Rosser, R. (1995). Functional aspects of recollective experience in face recognition. *Consciousness and Cognition,* **4**, 387-398.

* Perfect, T. J. & Dasgupta, Z. R. R. (1997). What underlies the deficit in reported recollective experience in old age? *Memory & Cognition,* **25**, 849-858.

* Perfect, T. J., Williams, R. B., & Anderton-Brown, C. (1995). Age differences in reported recollective experience are due to encoding effects, not response bias. *Memory,* **3**, 169-186.

Raaijmakers, J. G. & Shiffrin, R. M. (1992). Models for recall and recognition. *Annual Review of Psychology,* **43***,* 205-234.

* Rajaram, S. (1993). Remembering and knowing: Two means of access to the personal past. *Memory & Cognition,* **21**, 89-102.

Rajaram, S. (1996). Perceptual effects on remembering: Recollective processes in picture recognition memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **22**, 365-377.

Rajaram, S. (1998). Conceptual and perceptual effects on remembering: The role of salience/distinctiveness. *Psychonomic Bulletin & Review*, **5**, 71-78.

Rajaram, S. (1999). Assessing the nature of retrieval experience: Advances and challenges. In, B. H. Challis & B. M. Velichkovsky (Eds.), *Stratification in cognition and consciousness* (pp. 255-275). Amsterdam: John Benjamins.

Rajaram, S. & Roediger, H. L. (1997). Remembering and knowing as states of consciousness during retrieval. In, J. D. Cohen & J. W. Schooler (Eds.), *Scientific approaches to consciousness* (pp. 213-240). Mahwah, NJ: Erlbaum.

Richardson-Klavehn, R., Gardiner, J. M., & Java, R. I. (1996). Memory: Task dissociations, process dissociations and dissociations of consciousness. In, G. Underwood (Ed.), *Implicit cognition* (pp. 85-158). Oxford: Oxford University Press.

Roediger, H. L. & Blaxton, T. A. (1987). Effects of varying modality, surface features, and retention interval on priming in word-fragment completion. *Memory & Cognition,* **15**, 379-388.

* Schacter, D. L., Koutstaal, W., Johnson, M. K., Gross, M. S., & Angell, K. E. (1997). False recognition induced by photographs: A comparison of older and younger adults. *Psychology and Aging,* **12***,* 203-215.

Tulving, E. (1985). Memory and consciousness. *Canadian Psychology,* **26**, 1-12.

* Wagner, A. D., Gabrieli, J. D. E., & Verfaellie, M. (1997). Dissociations between familiarity processes in explicit recognition and implicit perceptual memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **23**, 305-323.

Wagner, A. D. & Gabrieli, J. D. E. (1998). On the relationship between recognition familiarity and perceptual fluency: Evidence for distinctive mnemonic processes. *Acta Psychologica,* **98**, 211-230.

Wagner, A. D., Stebbins, G. T., Masciari, F., Fleischman, D. A., & Gabrieli, J. D. E. (1998). Neuropsychological dissociation between recognition familiarity and perceptual priming in visual long-term memory. *Cortex,* **34**, 493-511.

Wolters, G. & Prinsen, A. (1997). Full versus divided attention and implicit memory performance. *Memory & Cognition,* **25**, 764-771.

Yonelinas, A. P. & Jacoby, L. L. (1995). The relation between remembering and knowing as a basis for recognition: Effects of size congruency. *Journal of Memory and Language,* **34**, 622-643.

APPENDIX A

Minimum RMSD of each Group of Models for Comparisons of Age

Study	Exp.	Condition	Group I	Group II	Group III
Fell (1992)		Shallow encoding	0.088	0.255	0.015
		Deep encoding	0.008	0.014	0.005
Friedman & Trott (2000)			0.013	0.007	0.030
Jacoby, Jennings, & Hay (1996)			0.003	0.078	0.050
Java (1996)			0.024	0.014	0.065
Mark & Rugg (1998)			0.006	0.007	0.005
Maylor (1995)	1		0.021	0.018	0.046
Norman & Schacter (1977)	1	No explanation	0.032	0.028	0.030
		Explanation	0.022	0.028	0.015
Parkin & Walter (1992)	1		0.019	0.148	0.055
	2		0.023	0.060	0.051
Perfect & Dasgupta (1997)	1	Words	0.050	0.033	0.093
		Nonwords	0.037	0.056	0.106
Perfect, Williams, & Anderton-Brown (1995)	1		0.055	0.212	0.025
	2b		0.033	0.229	0.170
Schacter, Koutstaal, Johnson, Gross, & Angell (1997)	1	1 repetition	0.012	0.014	0.055
		3 repetitions	0.018	0.000	0.045
	2		0.096	0.049	0.130

APPENDIX B

Minimum RMSD of each Group of Models for Comparisons of Level of Processing

			Group		
Study	Exp.	Condition	I	II	III
Fell (1992)		Young subjects	0.023	0.088	0.105
		Old subjects	0.012	0.393	0.085
Gardiner (1988)	1		0.064	0.014	0.110
Gregg & Gardiner (1994)	1	Auditory	0.050	0.035	0.100
		Visual	0.071	0.057	0.130
Java, Gregg, & Gardiner (1997)	2		0.022	0.085	0.045
Khoe, Kroll, Yonelinas, Dobbins, & Knight (2000)	1	Yes-No	0.059	0.035	0.075
		Forced Choice	0.027	0.035	0.055
Macken & Hampson (1993)		1 repetition	0.012	0.021	0.060
		3 repetitions	0.056	0.021	0.090
		6 repetitions	0.033	0.000	0.065
Perfect, Williams, & Anderton-Brown (1995)	2a	Young subjects	0.072	0.050	0.105
		Old subjects	0.012	0.085	0.115
Rajaram (1993)	1		0.040	0.071	0.120

APPENDIX C

Minimum RMSD of each Group of Models for Comparisons of Divided Attention.

			Group		
Study	Exp.	Condition	I	II	III
Gardiner & Parkin (1990)	1	Focused/Div 1/Div 2	0.028	0.012	0.074
Mangels, Picton, & Craik (2001)		Focused/Easy/Hard	0.058	0.052	0.133
Parkin, Gardiner, & Rosser (1995)	1		0.025	0.005	0.060

APPENDIX D

Minimum RMSD of each Group of Models for Comparisons of Stimulus Modality

			Group		
Study	Exp.	Condition	IV	V	VI
Gregg & Gardiner (1994)	1	Deep encoding	0.011	0.021	0.047
	1	Shallow encoding	0.050	0.085	0.105
	2	Intentional/slow rate	0.005	0.021	0.039
	2	Incidental/fast rate	0.036	0.007	0.037
Rajaram (1993)	1		0.000	0.000	0.000
Wagner, Gabrieli & Verfaellie (1997)	4		0.130	0.156	0.104