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The Contribution of Recollection and Familiarity to Recognition and Source-Memory Judgments: A Formal Dual-Process Model and an Analysis of Receiver Operating Characteristics

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A formal dual-process model that assumes that memory judgments can be based on a threshold recollection process and a signal-detection-based familiarity process is proposed to account for both recognition and source-memory performance. The model was tested in 4 experiments by examining recognition and source-memory receiver operating characteristics (ROCs). In agreement with the predictions of the model, recognition and source memory dissociated in certain conditions. Recognition ROCs were curvilinear in probability space and relatively linear in *z*-space, as expected if recollection and familiarity contributed to performance. In contrast, source ROCs typically were linear and exhibited a pronounced U shape in *z*-space, as expected if performance primarily relied on recollection. However, in conditions in which familiarity was clearly indicative of an item's source, the source ROC became curvilinear, suggesting that participants could use familiarity as a basis for source judgments. Several alternative models, including the unequal-variance signal-detection model, were found to be inconsistent with the ROC data.

We have all had the experience of recognizing someone but not being able to recollect where or when we met the person before. Such examples are important in showing that recognition memory is not always accompanied by memory for source. Although we all experience such memory failures from time to time, some patient populations exhibit pronounced deficits in source-memory performance. For example, Schacter, Harbluk, and McLachlan (1984) found that amnesic patients had a particularly difficult time remembering source information. They presented made-up facts (e.g., Bob Hope's father was a fireman) to a group of amnesic patients and nonamnesic control participants. Later, the amnesic patients recalled as many "facts" as the control group did, but unlike the control group, they did not remember having encountered these facts in the experimental setting and reported that the facts must have come from some other source such as the TV or newspaper.

Similar dissociations between memory for occurrence and memory for source have been reported in studies of recognition memory. In these experiments, participants study items from two or more different sources (e.g., List 1 vs. List 2 or spoken by a man vs. a woman). In recognition tests, participants must discriminate between studied and nonstudied items, and in source-memory tests, participants must discriminate between items from the two different sources. Disproportionate deficits in source-memory performance compared with recognition-memory performance have been reported for amnesic patients (Hirst, 1982; Mayes, Meudell, & Pickering, 1985; Shimamura & Squire, 1991), patients with frontal lobe damage (Janowsky, Shimamura, & Squire, 1989), and very old populations (e.g., Ferguson, Hashtroudi, & Johnson, 1992; Hashtroudi, Johnson, & Chrosnaik, 1989; McIntyre & Craik, 1987; Mitchell, Hunt, & Schmitt, 1986; Schacter, Kaszniak, Kihlstrom, & Valderri, 1991). Moreover, forcing healthy participants to very rapidly make their memory judgments also leads to a disproportionate reduction in source-memory performance (Johnson, Kounios, & Reeder, 1994).

The dissociations that have been observed between recognition and source memory for memory-impaired patients are so compelling as to tempt one to say that memory for source relies on a separate type of memory or a separate memory process from that supporting recognition performance and perhaps that a "source-memory process" is selectively disrupted in these patients. However, yielding to this temptation is to identify a memory task with an underlying process or system. The problem is that memory tasks are not always process-pure (e.g., see Bowers & Schacter, 1990; Jacoby, Toth, & Yonelinas, 1993; Richardson-Klavehn & Bjork, 1988; Toth, Reingold, & Jacoby, 1994). Thus, performance on recognition and source-memory tasks may not provide pure measures of separate memory processes. In this article, I argue that it is a mistake to treat recognition and source-memory tasks as providing pure measures of separate memory processes and that both tasks can be understood in

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terms of a dual-process theory that has been useful in accounting for standard recognition-memory tasks.

Dual-Process Theories and Source-Memory Performance

Dual-process theories of recognition postulate that there are two qualitatively different processes (i.e., recollection and familiarity) that underlie memory judgments. This notion dates back to Aristotle but has been expanded by several contemporary cognitive psychologists (e.g., Atkinson & Juola, 1974; Huppert & Piercy, 1976; Jacoby & Dallas, 1981; Mandler, 1980). Familiarity is assumed to be a relatively fast process that reflects the global familiarity or strength of an item. The idea is that items that have been studied will be more familiar than those that have not, and thus participants can accept the more familiar items as having been studied. However, participants are not limited to assessments of familiarity. If they can recollect some aspect of the study event (e.g., "I remember seeing that word. . . . It was the first one in the list."), this also could serve as a basis for recognition judgments. Recollection is generally assumed to be a search process whereby qualitative information about the study event is retrieved.

Several different methods have been developed for separating the contributions of recollection and familiarity (e.g., see Atkinson & Juola, 1974; Jacoby, 1991; Tulving, 1985). A growing body of literature has used these methods to examine the behavioral (e.g., Jacoby, 1991; Toth, 1996), electrophysiological (e.g., Düzel, Yonelinas, Mangun, Heinze, & Tulving, 1997), and neuroanatomical nature of recollection and familiarity (e.g., Yonelinas, Kroll, Dobbins, Lazzara, & Knight, 1998) and has shown that these two processes differ in numerous critical ways. Although a review of these findings is beyond the scope of this article, several of the behavioral results are directly relevant to the present discussion of source memory. First, amnesic patients are able to make recognition judgments on the basis of assessments of familiarity but often perform close to chance level on recognition tasks that require recollection (e.g., Huppert & Piercy, 1978; Verfaellie & Treadwell, 1993; Yonelinas et al., 1998). Similarly, aged participants (e.g., Jennings & Jacoby, 1993; Parkin & Walter, 1992) and patients with frontal lobe lesions (Wheeler, Stuss, & Tulving, 1997) show disproportionate reductions in recollection. Moreover, recognition judgments based on familiarity tend to be faster than those based on recollection (e.g., Atkinson & Juola, 1974; Mandler & Boeck, 1974; Toth, 1996; Yonelinas & Jacoby, 1994).

Given the similarity of the recognition and source-memory tasks, one may expect that they tap into similar underlying processes. However, if this were true, then why does source-memory performance dissociate from recognition performance? The answer provided by dual-process theories is that source-memory tasks rely less on familiarity than does recognition, which because it involves discriminating between studied (familiar) and nonstudied (unfamiliar) items can be based on familiarity as well as recollection. In contrast, because familiarity cannot be used to determine the source of two equally familiar (both studied) items, source memory must depend on the recollection of aspects of the study event that link it to its source. Because source-memory tasks primarily rely on recollection whereas recognition tasks rely on both recollection and familiarity, recognition and source-memory performance could dissociate.

Support for the notion that source judgments heavily rely on recollection comes from a comparison of the dual-process and source-memory literatures. For example, as already discussed, both source-memory performance and recollection are disrupted in amnesic patients, patients with frontal lobe damage, and very old populations. Similarly, response deadline leads to pronounced reductions in both source-memory performance and recollection.

Although the similarities seen in the source-memory and dual-process literatures suggest that source judgments heavily rely on recollection, it is likely that source-memory tasks do not always exclusively rely on recollection. That is, familiarity also may contribute to source-memory judgments. To see why, imagine that one list of words was presented 5 days ago and a second list of words was presented 5 min ago. The items from the more recent list would likely be the most familiar, and thus a high level of familiarity associated with a test item could be attributed to the item's occurrence in the second list. Hoffman (1997) recently tested this notion and found that when the memory strengths of the items from one source were greater than those from the other, participants could use familiarity as a basis for source judgments. Similarly, perceptual fluency may serve as a basis for source judgments. For example, Kelley, Jacoby, and Hollingshead (1989) found that when the items from one source were more perceptually fluent than those from another source (i.e., same modality vs. different modality at study and test), there was a dependent relationship between perceptual identification and judgments of study modality. However, when participants were given a mnemonic to encode source information, they no longer had to rely on the assessment of fluency, and the dependency between perceptual identification and source memory was no longer observed.

The effects of familiarity-based source judgments will be examined in the current study. However, in most previous studies of source memory, the items from the different sources were approximately equal in terms of familiarity, and it is likely that source-memory performance relied less heavily on familiarity than did recognition memory. Thus, the dissociations observed between recognition and source-memory tasks are consistent with the dual-process framework.

A Dual-Process Signal-Detection Model

To test more rigorously the claim that recognition and source memory can be understood in the dual-process framework, it is useful to develop a formal model. First, I describe a dual-process signal-detection model that was designed to account for recognition memory (Yonelinas, 1994) and briefly discuss the assumptions underlying this model. The empirical evidence in support of these assumptions is discussed in more detail after the results of the present experiments are presented. Second, I describe how the model can be applied to source-memory tasks and explain the predictions that it makes about source-memory performance. I also describe an alternative model that has been used quite extensively in studies of human memory (i.e., the unequal-variance signal-detection model) and discuss its predictions.

The dual-process signal-detection model is based on the notion that familiarity reflects a signal-detection process and recollection reflects a threshold retrieval process. The idea of incorporating signal-detection theory into a dual-process model was first proposed by Atkinson and Juola (1974) and was later suggested as a way of describing the automatic influences of memory in a stem-completion task (Jacoby et al., 1993). In the present recognition model, familiarity is assumed to be well described by the classical signal-detection model that underlies d' reference tables—that is, a Gaussian equal-variance signal-detection model. The idea is that participants can place items on a familiarity continuum such that studied items fall on the high end of the continuum and new items fall on the low end of the continuum. However, there is some variability from one item to the next such that the familiarity values associated with old and new items are normally distributed (i.e., Gaussian) and overlap each other, as shown in Figure 1. The distance between the means of the two distributions is measured as a z score and is referred to as d'. To discriminate between old and new items, participants must select some level of familiarity (i.e., a response criterion) so that only the items exceeding this level are accepted as old. So, for example, in Figure 1, the probability of accepting an old item on the basis of familiarity is equal to the proportion of the old-item distribution that exceeds the response criterion. Because the old- and new-item distributions are assumed to have the same variance, familiarity is described as an equal-variance signal-detection process.

In contrast to familiarity, recollection is assumed to reflect a threshold retrieval process whereby participants retrieve qualitative information about the study event. Because participants can either succeed or fail to retrieve information about an event, recollection is measured as a probability rather than as a d' value. Of course, participants can recollect different aspects or different amounts of information about the study event, such as information about the physical context or what they were thinking about when the event occurred. Most important, however, is that there exists a threshold below which there is no recollective information available to the participants that supports accurate discrimination between studied and nonstudied items. Participants are free to accept items that fall below the threshold but, in the absence of familiarity, doing so amounts to a form of guessing because such a strategy is equally likely to lead to a false recognition as it is to a true recognition.

If the products of recollection and familiarity are independent, then the probability of recognizing a target item (i.e., a studied item) is equal to the probability that it is recollected (R_t) plus the probability that the item is not recollected ($1 - R_t$) but its familiarity exceeds the response criterion (F_t):

$$p(\text{"yes"}|\text{target}) = R_t + (1 - R_t)F_t. \quad (1)$$

Given that the participant adopts a particular response criterion, he or she also will accept a certain proportion of the lure items (i.e., nonstudied items). The probability of incorrectly accepting a lure item is equal to the probability that its familiarity exceeds the response criterion (F_l):

$$p(\text{"yes"}|\text{lure}) = F_l. \quad (2)$$

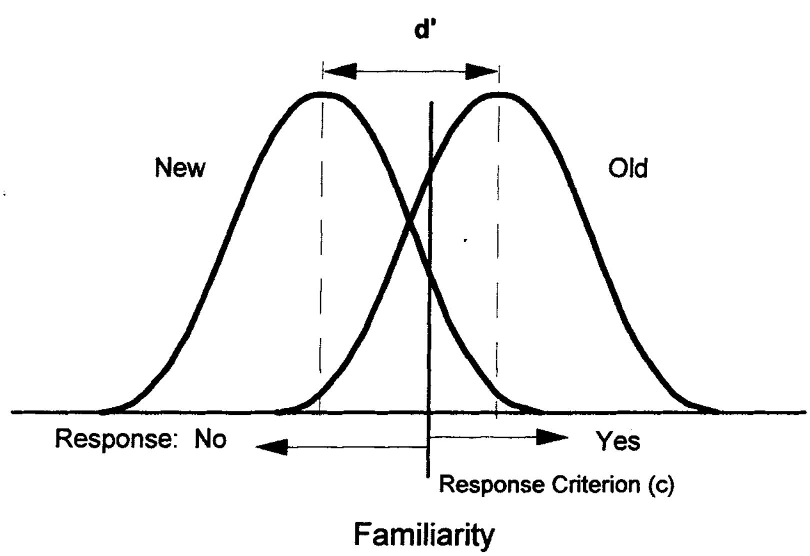

Figure 1. Familiarity distributions for old and new items for the equal-variance signal-detection model.

Equations 1 and 2 can be combined (subtract Equation 2 from Equation 1, then move the familiarity term from the left side of the equal sign to the right side) to arrive at a single function that relates the hit rate to the false-alarm rate:

$$p(\text{"yes"}|\text{target}) = p(\text{"yes"}|\text{lure}) + R_t + (1 - R_t)F_t - F_l. \quad (3)$$

If the familiarity distributions are normal and of equal variance, then $F_t = \Phi[(d'/2) - c]$ and $F_l = \Phi[-(d'/2) - c]$. The Φ functions represent the proportions of the target and lure distributions that exceed the response criterion (c), given that the distance between the means of the two Gaussian distributions is d'. See Macmillan and Creelman (1991) for a thorough discussion of signal-detection theory. By substituting these two equations into Equation 3, it is possible to represent the relationship between hits and false alarms as

$$p(\text{"yes"}|\text{target}) = p(\text{"yes"}|\text{lure}) + R_t + (1 - R_t)\Phi[(d'/2) - c] - \Phi[-(d'/2) - c]. \quad (4)$$

Note that an important assumption underlying the dual-process model represented in Equation 4 is that relaxing the response criterion influences only familiarity-based responses; correct recollection does not change as the response criterion is relaxed. This assumption is meant to capture the notion that when participants correctly recollect qualitative information about a previous event, they should be quite confident that the event actually occurred. Thus, changes in the response criterion that lead to differences in the proportion of items accepted on the basis of familiarity should have very little effect on estimates of recollection. In the General Discussion section, I consider conditions under which it may be necessary to relax this assumption and suggest how the model might be expanded to accommodate such changes. However, as I will show, Equation 4 provides a very good approximation for the existing recognition data, suggesting that the model's assumptions are reasonable.

Expressing the model as a single equation that relates hits to false alarms (i.e., Equation 4) is useful because then it is possible to assess whether the model accurately describes the observed relationship between hits and false alarms. This fundamental relationship is referred to as the receiver operating characteristic (ROC). One way of generating an ROC is to vary the response criterion (c) while memory (R and d') is kept constant. For example, Figure 2A (left panel) shows the predicted ROC when both recollection and familiarity contribute to performance. The predicted function is curvilinear and asymmetrical along the diagonal. The asymmetry is typically measured by plotting the function on *z*-coordinates (i.e., a *z*-ROC) and measuring the slope. A perfectly symmetrical ROC has a slope of 1.0 when plotted in *z*-coordinates. The *z*-ROC in Figure 2A has a slope of approximately 0.75.

Recognition-memory ROCs are typically examined by requiring participants to report the confidence of their recognition judgments, and performance is then plotted as a function of confidence (e.g., see Donaldson & Murdock, 1968; Egan, 1958; Gehring, Toglia, & Kimble, 1976; Glanzer & Adams, 1990; Murdock & Dufty, 1972; Ratcliff, Sheu, & Gronlund, 1992). In agreement with the dual-process model, the recognition-memory ROCs are curved and asymmetrical, as in Figure 2A. However, beyond accurately describing the general shape of the ROCs, the model can account for dissociations between the ROC asymmetry and accuracy that are often observed. That is, in some cases, as accuracy increases, the degree of asymmetry in the function remains constant (e.g., Egan, 1958; Ratcliff, McKoon, & Tindall, 1994; Ratcliff et al., 1992; Yonelinas, 1994; Yonelinas & Jacoby, 1995). In other cases, as performance increases, the ROC becomes more asymmetrical (e.g., Donaldson & Murdock, 1968; Glanzer & Adams, 1990; Ratcliff et al., 1994). Although this pattern of results is problematic for several memory models (see Ratcliff et al., 1992), such as the theory of distributed associative memory (TODAM; Murdock, 1982), the search of associative memory model of recall (Gillund & Shiffrin, 1984), and MINERVA 2 (Hintzman, 1986), the dual-process model can account for the observed dissociations in the following way. If recollection alone increases, then performance will increase, and the ROC will become more asymmetrical. In contrast, if both recollection and familiarity increase together, then it is possible for performance to increase while the degree of ROC asymmetry remains constant. For a detailed discussion of ROC asymmetry and the dual-process model, see Yonelinas (1994) and Yonelinas, Dobbins, Szymanski, Dhaliwal, and King (1996).

Recognition ROCs also can be fit quite well by another very simple model: the unequal-variance signal-detection model. That is, if memory judgments are based on familiarity (or memory strength), as shown in Figure 1, but the variance of the old-item distribution is greater than that of the new-item distribution (i.e., the distribution on the right side of Figure 1 is wider than the distribution on the left side), then the signal-detection model predicts an asymmetrical ROC, as shown in Figure 2D. If d' increases and the variance of the old-item distribution (V_o) also increases, then performance will increase, and the ROC will become more asymmetrical. In contrast, if d' increases while the variance of the old-item distribution remains constant, then performance will increase, and the degree of asymmetry will remain constant.

A comparison of Figures 2A and 2D shows that the dual-process model and the unequal-variance model can produce very similar ROCs. Note that both models require only two free memory parameters to produce an ROC. The dual-process model requires one parameter for recollection (R) and one for familiarity (d'). The unequal-variance model requires one parameter for discrimination (d') and one for the old-item variance (V_o; this assumes that the variance of the new-item distribution is equal to 1.0).

There is, however, an important difference between these two models. Because the dual-process model assumes that a threshold process contributes to performance, it predicts a slightly flatter ROC than the pure signal-detection model. In

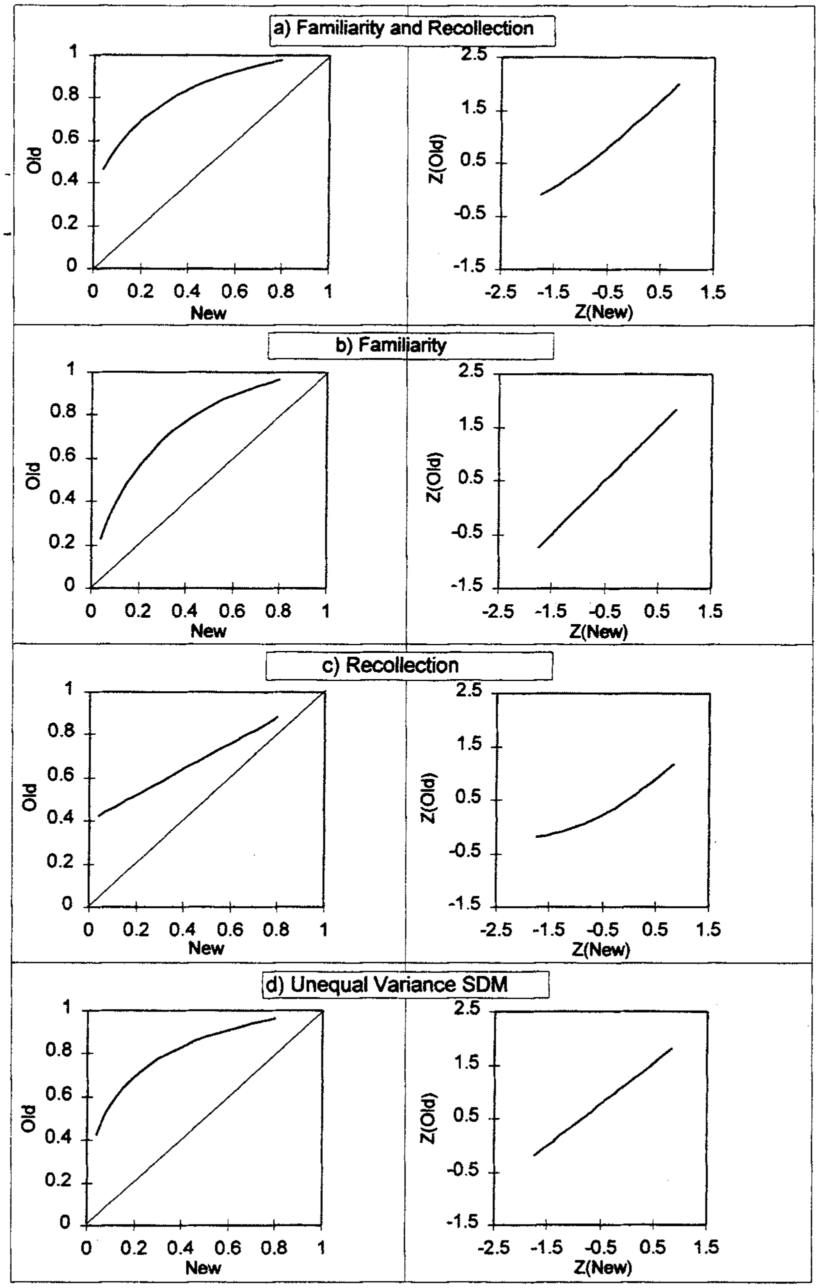

Figure 2. Predicted receiver operating characteristics (ROCs) for (a) the dual-process signal-detection model, (b) the equal-variance signal-detection model, (c) the threshold model, and (d) the unequal-variance signal-detection model (SDM). The ROCs are plotted in probability space and *z*-space in the left and right panels, respectively.

standard recognition-memory tasks, the difference is so subtle (e.g., compare Figures 2A and 2D) that it is difficult to discriminate between the models (see Yonelinas, 1994; Yonelinas et al., 1996; but also see Glanzer, Kim, Hilford, & Adams, 1999; Yonelinas, 1999). However, the models should be easily discriminated in conditions in which recollection is expected to play a predominant role in performance. If the dual-process model is correct, then when performance relies primarily on recollection, the ROCs should become relatively linear. Figure 2C shows the ROC predicted by the model when only recollection plays a role in performance. Most important is that when the ROC is plotted in *z*-space, it exhibits a pronounced U shape. In contrast, the unequal-variance model predicts a curved ROC (as long as performance is above chance level), and it always predicts a linear *z*-ROC. The experiments in this article serve to more closely contrast the dual-process and unequal-variance models in conditions in which performance is expected to primarily rely on recollection (i.e., tests of source memory). The unequal-variance model predicts that the z-ROCs should always be linear. In contrast, the dual-process model predicts that there should be cases in which the z-ROCs are U-shaped.

A Dual-Process Model of Source-Memory Performance

Previous tests of the dual-process model have focused on recognition-memory performance. In contrast, the present study aimed to determine if the model can be generalized to account for source-memory performance. Examining source ROCs is important for several reasons. First, although a great deal is known about recognition-memory ROCs, source ROCs have not been examined.[1] Such an analysis has proved to be extremely useful in testing models of recognition memory (e.g., see Murdock, 1974; Ratcliff et al., 1992), and it is likely that it also will prove to be useful in understanding the processes that underlie source-memory tasks. Second, the dual-process model makes some novel predictions about what the source ROCs should look like (i.e., U-shaped z-ROCs), and these predictions contrast with most existing ROC findings on recognition memory. If the model generates novel predictions about source memory that are found to be correct, and if the model is found to provide an accurate account of both the recognition and source-memory ROCs, it would provide strong support for the model and show that both tasks can be understood in the same theoretical framework. Third, as previously discussed, the model makes predictions that differ from those of the unequal-variance signal-detection model in conditions in which recollection plays a dominant role in performance. Thus, source-memory ROCs may prove to be useful in contrasting these two models. Note that the unequal-variance model represents an attractive alternative because it has been used extensively in studies of recognition memory, and Hoffman (1997) recently showed that there are conditions in which signal-detection theory is very useful in understanding standard source-memory judgments, although this research did not examine ROCs (also see Marsh & Bower, 1993).

Although the dual-process model can produce linear ROCs, it is important to note that perfectly linear source ROCs should be observed only if the source-memory task provides a pure measure of recollection. If familiarity also contributes to source-memory judgments, then the source functions should become curvilinear. The following studies examined source ROCs in conditions in which the use of familiarity to determine source was either encouraged or discouraged, to determine if the curvilinearity of the source functions could be controlled. Although it may not be possible to find conditions in which source memory relies exclusively on recollection, when familiarity is discouraged, the source ROCs should be relatively linear in comparison with the curvilinear functions observed in recognition, and the source ROCs should exhibit a noticeable U shape when plotted in z-space.

Beyond testing the qualitative predictions of the dual-process model, it was desirable to determine how well the model fit the observed ROCs. To do so, a generalized form of the dual-process model was developed that could be used to describe recognition as well as source-memory ROCs. The generalized model was identical to that used in previous recognition studies except that it allowed for the probability that participants could recollect items from two different study lists rather than from a single study list. The equation for the hit rate is the same as that used in recognition memory. In the source-memory test, I refer to the items from one source as the "target items" and the items from the other source as the "lure items." Thus, an item from a target source is correctly accepted as originating from that source if its source is recollected (R_t) or if it is not recollected ($1 - R_t$) but is accepted on the basis of familiarity (F_t):

$$p(\text{"yes"}|\text{target}) = R_t + (1 - R_t)F_t. \quad (5)$$

In contrast, an item from the lure source is incorrectly accepted as originating from the target source only if its true source is not recollected ($1 - R_l$) and it is sufficiently familiar (F_l):

$$p(\text{"yes"}|\text{lure}) = (1 - R_l)F_l. \quad (6)$$

That is, if participants recollect that an item was from the lure source, they should not falsely accept it as coming from the target source. This assumes that there were no items that were in both sources, which is typical of most source-memory experiments.

The signal-detection equations presented earlier can be combined with Equations 5 and 6 to form the following equation that describes the relationship between hits and false alarms:

$$p(\text{"yes"}|\text{target}) = p(\text{"yes"}|\text{lure}) + R_t + (1 - R_t) \cdot \Phi[(d'/2) - c] - (1 - R_l)\Phi[-(d'/2) - c]. \quad (7)$$

The generalized model requires three free memory parameters (R_t, R_l, and d') in comparison with the standard recognition model that requires only two (R_t and d'). Note that the recognition model is a submodel of the generalized model, in which R_l equals zero. I refer to specific submodels of the general dual-process model (i.e., Equation 7) in terms of the memory parameters used in the submodel. For example, the standard dual-process model is referred to as (R_t, d'), indicating that there is one recollection parameter and one familiarity parameter and that the second recollection parameter (R_l) is set to zero.

There should be conditions in which all three parameters are required to describe the source-memory ROC (i.e., when recollection and familiarity contribute to performance and the probability of recollecting items from the two sources differs). However, the number of required parameters may

[1] This study was presented at the 37th Annual Meeting of the Psychonomic Society, Chicago, Illinois, 1996. Wayne Donaldson also reported similar source-memory results at that meeting.

be reduced in several ways. Most important, if source judgments primarily rely on recollection, then the discrimination afforded by familiarity (i.e., d') should approach zero. Because d' equals zero, the familiarity terms—that is, $\Phi[(d'/2) - c]$ and $\Phi[-(d'/2) - c]$—are equal, and they can be replaced by a single guessing or criterion term (the probability of accepting an old or a new item at a given criterion). In this way, the dual-process model collapses into a model that requires only two memory parameters (i.e., R_t and R_l), and the model then predicts a linear ROC. The source ROC may become linear if the familiarity distributions for the items from the two sources do not differ (i.e., the items from the two sources are equally familiar). If this occurs, then regardless of the participants' response criterion, the probability that an item's familiarity exceeds the response criterion will be equal for items from the two sources. In this case, familiarity is still used as a basis for responding, and it would lead to a range of response confidence judgments in exactly the same way that it does in standard signal-detection theory, but it would not contribute to the discrimination between items from the two sources, and thus it would amount to a form of guessing. Alternatively, participants may simply ignore familiarity when source recollection fails and base their responses on some other nonmnemonic response strategy. This could involve random guessing (i.e., responses to nonrecollected items are distributed across the range of confidence categories) or any other strategy for responding to items that they do not recollect (see Murdock, 1974, pp. 18–26). In any case, when familiarity does not accurately discriminate between items from two different sources, this can be represented by setting d' in Equation 7 equal to zero, and it will result in a linear ROC.

The model may be simplified further if familiarity does not contribute to source discrimination and the probability of recollecting items from the two sources is equal. In this case, the model requires only one memory parameter (i.e., R).

It is important to note that the estimates of recollection and familiarity in a source-memory test are not expected to be identical to those in a recognition-memory test. For example, in a source-memory test, only recollected information that links an item to a specified source (e.g., List 1) serves as recollection. In a recognition test, any recollected information that links the item to the study phase of the experiment serves as recollection. Recognition-memory tests may be thought of as being more inclusive than source-memory tests, and thus the parameter estimates for recollection in a recognition test may be greater than those in a source test. Note, however, that like source-memory tests, recognition tests do not provide a completely inclusive measure of recollection. For example, a participant may recollect having encountered an item outside of the experimental context, and this will not serve as recollection in the recognition or source-memory test (e.g., see Gruppuzo, Lindsay, & Kelly, 1997; Mulligan & Hirshman, 1997; Wagner, Gabrieli, & Verfaellie, 1997; Yonelinas & Jacoby, 1996, for further discussions of such noncriterial recollection). Similarly, the estimate of familiarity in a recognition-memory test is not expected to be the same as that in a source-memory test. For example, the difference in familiarity between new and old items in a recognition test may not be the same as the difference in familiarity between items from two different sources.

Moreover, the retrieval demands of the memory task may influence what information is retrieved from memory (e.g., see Johnson, Hashtroudi, & Lindsay, 1993), and this may lead to further differences in the parameter estimates of recollection and familiarity in the recognition and source-memory tasks. For example, in a recognition test, participants may recollect things about an event that they would not recollect if they were in a source-memory test. Moreover, they may not recollect information about source if they are not explicitly instructed to remember source information.

The Present Experiments

The primary aim of this study was to determine whether recognition and source memory could be dissociated in terms of the shapes of their respective ROCs. If the dual-process model is correct, then the recognition ROCs should be curvilinear in probability space and relatively linear in *z*-space. Most important, however, there should be cases in which source-memory judgments are driven primarily by recollection, and thus the source ROCs should be relatively linear in probability space and U-shaped in *z*-space. In contrast, the unequal-variance signal-detection model predicts that the ROCs should be curvilinear in probability space and should always be linear in *z*-space.

This study includes four experiments that were designed to examine recognition and source-memory ROCs in a variety of study and test conditions. Participants studied words from two different sources and then were given recognition and source-memory tests, in which they were required to rate the confidence of their memory responses. The recognition and source ROCs were then plotted in probability space as a function of response confidence, and the dual-process model was fit to the functions to determine if it could account for the general shape of the observed ROCs. A linearity analysis was then conducted to determine if the observed functions were nonlinear. The ROCs were then replotted in *z*-space, and a second linearity analysis was conducted to determine if the *z*-ROCs were nonlinear.

Experiment 1

Experiment 1 examined recognition and source-memory ROCs in conditions designed to make it difficult for participants to use familiarity as a basis for source-memory judgments and such that the probability of recollection was roughly equal for items from the two different sources. Words were presented one at a time on the left and the right side of the computer screen in a random order. Participants were instructed to remember all the words and to try to remember the side of the screen on which each word was presented. After studying the list of words, half of the participants received a test of recognition memory, and half received a test of source memory. For the recognition test, participants were presented with a mixture of studied and nonstudied items and were required to make recognition judgments on a 6-point confidence scale ranging from *sure it was new* to *sure it was old.* For the source-memory test, participants were presented with words from the study list and were required to make left–right judgments on a 6-point confidence scale ranging from *sure it was on the left* to *sure it was on the right.*

Because the words from the two sources were mixed randomly at study and participants were instructed to remember all the words, items from the two sources should be equally familiar. In this way, familiarity should not be very useful in discriminating between the items from the two sources, and performance should rely primarily on recollection. Thus, the source ROC should be relatively linear, and the *z*-ROC should be U-shaped. Moreover, because recollection of the two sources should be approximately equal, a one-parameter version of the dual-process model (R) should account for the source ROC. In contrast, for recognition memory, both recollection and familiarity were expected to contribute to performance. Thus, the recognition ROC was expected to be curvilinear and asymmetrical, and the standard recognition model (R_t, d') was expected to fit the ROC.

Method

Participants and materials. Forty undergraduates participated in the experiment for credit in an introductory psychology course. Words were randomly selected from the Toronto word pool for each participant.

Design and procedure. Materials were presented and responses collected on a PC-compatible computer. The viewing distance was approximately 0.5 m. Each participant was tested individually. The study phase was the same for all participants. At the beginning of the session, participants were informed that they would be presented with a list of words on the computer screen, in which half of the words would be presented on the left side of the screen and half on the right. They were told to try to remember the words that were presented and on which side of the screen they were presented. Pilot studies showed that many participants performed very poorly on the source-memory task. To improve performance, participants were instructed to try to remember the source by associating the words from the two sources with two distinctive people. One hundred and twenty words were presented one at a time at a 3-s rate. The side of the screen that words were presented on was randomized.

Immediately after the study phase, participants received either a recognition-memory test or a source-memory test. The words were presented in a random order, one at a time, in the middle of the screen. Half of the participants received a recognition test containing all of the words from the study list (60 from the left and 60 from the right) and 120 new words. Participants were instructed to judge whether the words were presented in the study list. If they thought the word was in the study list (from either side of the screen), they were to press *4, 5,* or *6* on the keyboard: *6* if they were sure it was studied, *5* if they were less sure, and *4* if they were very unsure. If they thought the word was new, they were to respond by pressing *1, 2,* or *3* on the keyboard: *1* if they were sure the word was new, *2* if they were less sure, and *3* if they were very unsure.

The other half of the participants received a source-memory test in which all of the words from the study list were presented one at a time in a random order. Participants in the source-memory test were instructed to judge whether the words had been presented on the left or the right side of the screen at the time of study and to rate how confident they were about each judgment. If they thought the word was on the right, they were to press *4, 5,* or *6* on the keyboard: *6* if they were sure it was on the right, *5* if they were less sure, and *4* if they were very unsure. If they thought the word was studied on the left, they were to press *1, 2,* or *3* on the keyboard: *1* if they were sure it was on the left, *2* if they were less sure, and *3* if they were very unsure. Participants were informed that no words were presented on both sides of the screen and that all of the test items had been studied.

All participants were told to try to use the entire range of response keys. Each word remained on the screen until the participant responded. After a 500-ms delay, the next test word appeared. The experimental session took approximately 30 min to complete.

Analysis. The ROCs were fit to the dual-process model by using a nonlinear regression method that minimized the sum of square error (SSE) between the predicted function (Equation 7) and the observed ROC points. For recognition memory, R_l in Equation 7 was set to zero. For source memory, d' was set to zero, and R_l was set equal to R_t. Because the function could be nonlinear and the points varied on the *x*- and *y*-axes, the SSE term reflected variation in both hits and false alarms. The details of the method have been described elsewhere (Yonelinas et al., 1998), and the search algorithm that was used is available on request. A similar method based on a maximum-likelihood estimation procedure also was used to fit the model to the data in all of the experiments. However, the fits for the two methods were very similar; thus, only the results for the SSE analysis are reported.

Linearity analyses of the ROCs and the *z*-ROCs were conducted in the following way. Standard linear regressions were conducted to determine whether the functions exhibited significant linear trends. A quadratic term was then introduced to the linear equation to determine whether there was a significant curvilinear component. A function is referred to as "linear" if the regression analysis showed that it exhibited a significant linear trend and introducing the quadratic component did not lead to a significant improvement in the fit of the equation. In contrast, if the quadratic component did lead to a significant improvement in the fit of the equation, the function is referred to as "curvilinear." Because the quadratic equation is not symmetrical along the negative diagonal, the fit of the equation can be slightly different if *x* is regressed onto *y* than if *y* is regressed onto *x*. Because the *x*- and *y*-axes in an ROC are arbitrary, the quadratic was fit in both directions to determine the best fitting nonlinear function, and it was this fit that was compared with the linear fit.

Three points should be made about the linearity analysis. First, there are other nonlinear equations that could have been used to assess curvilinearity and other methods for assessing linearity. However, the present method was chosen because (a) it is commonly used in this context, (b) it can be used to assess functions in probability space and *z*-space, (c) it is relatively theory-free in that it is not directly based on any one memory model, and (d) it provides a very good fit for the observed ROCs and *z*-ROCs. Second, the regression analysis assumes that the points in the function are independent. This assumption was not met in the present experiments because the ROCs were cumulated across response confidence. However, this should not be particularly problematic in the present context because the cumulative method used here has been found to lead to ROCs that are similar in shape to those observed when noncumulative methods are used (e.g., see Ratcliff et al., 1992). Third, the standard regression analysis allows for variation only along the *y*-axis. However, the

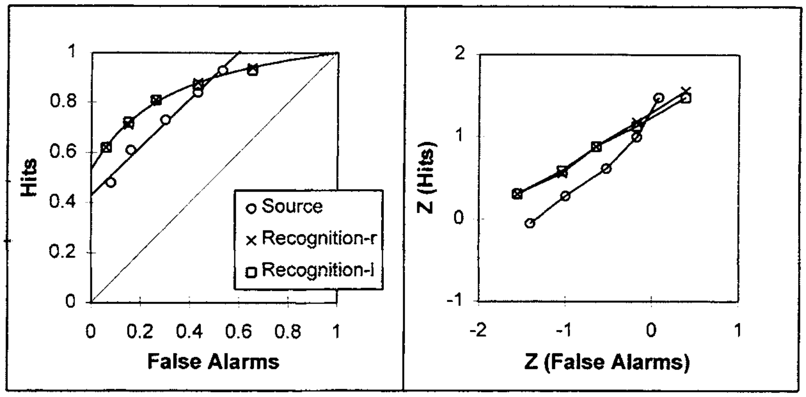

Figure 3. Recognition and source-memory receiver operating characteristics for Experiment 1, plotted in probability space and fit with the dual-process model (left panel) and plotted in *z*-space (right panel). Recognition performance is plotted separately for items that were studied on the left (l) and right (r) sides of the screen.

ROC points vary along both the *x*- and *y*-axes. To address this issue, an additional set of regression analyses were conducted in which the predicted points were allowed to vary in both dimensions, and these analyses led to conclusions that were similar to those of the standard regression method. There was only one case in which there was a minor disagreement between the two methods, which is discussed in Experiment 2, whereby the new method led to a conclusion that was more in keeping with the dual-process model than the unequal-variance model, compared with the standard regression method that did not favor one model over the other. Otherwise, the two methods led to the same conclusions; thus, only the results of the standard regression method are reported.

Results and Discussion

Receiver operating characteristics (ROCs). The significance level for the statistical tests in all of the experiments was $p < .05$. The average ROCs for Experiment 1 and the fit of the dual-process model are presented in Figure 3. The average hit rate is plotted against the average false-alarm rate as a function of response confidence (see Appendix A for the raw scores for all of the experiments). For the recognition task, the hit rate reflects the proportion of study items accepted as old, and the false-alarm rate reflects the proportion of new items accepted as old. Separate functions are plotted for the words that were studied on the left and the right side of the screen. However, because performance for the two types of items was almost identical, recognition performance was collapsed before it was analyzed and fit to the model. For the source-memory ROC, the hit rate reflects the proportion of words from the right side accepted as coming from the right side, and the false-alarm rate reflects the proportion of words from the left side accepted as coming from the right side.

An examination of Figure 3 shows that the dual-process model provided an accurate account of the observed recognition and source-memory functions (formal assessments of the model fits are described after the presentation of the four experiments). Model parameters are presented in Table 1. For recognition, two memory parameters were used to fit the function: R (i.e., the probability of recollecting a studied item) and d' (i.e., the difference in familiarity between the studied and nonstudied items). For source recognition, a one-parameter version of the model was fit to the function: R (i.e., the probability of recollecting the source of an item). Note that the left-most point on the source ROC fell slightly below the predicted function. This could be accommodated by the model if familiarity were allowed to contribute to performance. However, the deviation was quite small, and the analysis reported below suggests that the function did not deviate significantly from linearity.

A linearity analysis showed that the recognition and source-memory ROCs were fit well by curvilinear and linear functions, respectively. For the recognition ROC, there was a significant linear component, $R^2 = .9233$, $F(1, 3) = 36.13$, $MSE = 0.0016$. Most important, however, is that introducing the quadratic component led to a significantly better fit than that found with the linear equation, $R^2 = .9973$, $F(1, 2) = 53.96$, $MSE = 0.0014$, showing that the recognition function was curvilinear. For the source ROC, there was a significant linear component, $R^2 = .9904$, $F(1, 3) = 310.21$, $MSE = 0.0004$, and introducing the quadratic component did not

Table 1
Parameter Estimates of Recollection (R) and Familiarity (d′) for the Recognition and Source Tests

	Recognition test		Source test	
Experiment	R	d'	R[a]	d'
1	.49	.91	.42	
2	.33	.61	.22	
3				
Strong	.41	.45	.37/.19	
Weak	.26	.26		
4			.32/.05	.38

[a]Two recollection parameters (i.e., target/lure) are provided when the probability of recollecting items from the target and lure sources differed.

lead to a significant improvement over the linear equation, R^2 = .9983, $F(1, 2)$ = 9.08, MSE = 0.0002. Thus, in contrast to the recognition ROC, the source function was linear.

Could the ROCs have been influenced by averaging? Although averaging across participants or items could have influenced the shape of the functions, it is unlikely to have produced the differences that were observed between recognition and source memory, because artifactual effects of averaging would be expected to influence the recognition and source ROCs in the same way, making the two functions more similar. Nonetheless, the effect of averaging was examined by plotting ROCs for each participant and as a function of test position. An examination of individual participants' ROCs showed that the shape of the functions was not greatly influenced by averaging across participants. For recognition, 19 of the 20 participants exhibited an inverted U-shaped curve similar to the average recognition curve. For source memory, 16 participants exhibited relatively linear ROCs, 2 participants exhibited noticeable U-shaped curves, and 2 participants exhibited noticeable inverted U-shaped curves. ROCs also were examined as a function of test position (i.e., first vs. second half of the test list), and the linear and nonlinear aspects of the source and recognition functions were not found to change as a function of test position. Thus, averaging across participants and test position did not greatly influence the observed shapes of the ROCs.

Z-receiver operating characteristics (z-ROCs). To further assess the recognition and source data, the average ROCs were replotted on z-coordinates (see Figure 3). As expected, the average recognition z-ROC was relatively linear, and the source function was U-shaped. Linearity analyses supported these observations. For the recognition z-ROC, there was a significant linear component, R^2 = .9963, $F(1, 3)$ = 796.49, MSE = 0.0027, and the quadratic component did not provide a significant improvement over the linear function, R^2 = .9979, $F(1, 2)$ = 1.54, MSE = 0.0011, showing that the recognition z-ROC was linear. For the source z-ROC, there was a significant linear component, R^2 = .9635, $F(1, 3)$ = 79.29, MSE = 0.0177, and introducing the quadratic component provided a significant improvement in fit, R^2 = .9991, $F(1, 2)$ = 82.79, MSE = 0.0004, showing that the source function was curvilinear.

To quantify the asymmetry of the ROCs and to facilitate comparison with results from previous studies, the slopes and the intercepts of the best fitting linear functions for the z-ROCs were examined. The slope and intercept values for the recognition z-ROC were 0.65 and 1.27, respectively. The slope and intercept values for the source z-ROC were 0.98 and 1.26, respectively. Note, however, that because the source z-ROC in this experiment and in all the subsequent experiments was not linear, the slope and intercept values are not very meaningful.

In sum, the results show that recognition and source memory dissociated in terms of the shape of their ROCs. The recognition ROC was curvilinear in probability space and linear in z-space. In contrast, the source ROC was linear in probability space and exhibited a significant U shape in z-space. Thus, the recognition and source-memory results are in agreement with the predictions of the dual-process signal-detection model. Moreover, the source ROC was fit reasonably well by the predicted one-parameter submodel (R) of the general dual-process model, and the recognition ROC was fit well by the standard recognition submodel (R, d'). The recognition data were also consistent with the unequal-variance signal-detection model in the sense that the z-ROCs were relatively linear. However, the source-memory data were not consistent with the unequal-variance signal-detection model; the source z-ROCs were U-shaped, in contrast to the linear functions predicted by that model.

Experiment 2

Experiment 2 was designed to test the generalizability of the results from Experiment 1 by examining performance when source was defined in terms of list membership rather than in terms of study location. Words were presented in two lists; the first list was spoken by a man's voice and the second list by a woman's voice. The test phase was also different from that used in Experiment 1 in that the test list always included a mixture of new items and items from the two sources and participants were required to make a recognition and source-memory judgment for each item. These changes were not expected to greatly influence the ROCs, and the same recognition and source models were used to fit the data as in Experiment 1.

Method

Participants and materials. Twenty-four undergraduates participated in the experiment for credit in an introductory psychology course. Two hundred and forty words were randomly selected from the Toronto word pool. The words were randomly divided into three equal sets of items: spoken by a male voice, spoken by a female voice, and not spoken.

Design and procedure. Participants were tested in two groups of 12. In the study phase, participants heard a list of 80 words spoken by a male voice, followed by a list of 80 different words spoken by a female voice. Words were spoken at a rate of 1 word every 3 s. Participants were informed that they would be required to remember which words were presented and which words were spoken by which voice. Moreover, they were told that they should attend to words from both speakers because they were equally important.

Immediately after the study phase, participants received a recognition and source-memory test. They were given a test booklet containing a randomized mixture of the 80 words that had been spoken by the male voice, the 80 words spoken by the female voice, and 80 new words. There were two spaces beside each word in which participants were to write their responses. Participants were told that they were to make two different memory judgments for each word. First, they were to rate on a 6-point confidence scale how sure they were that the word was presented in the study phase. Participants were instructed to write down a number from 1 (*sure it was not studied*) to 6 (*sure it was studied*) in the first space beside each word. Second, participants were instructed to make a source judgment for each word. They were instructed to write down a number from 1 (*sure it was spoken by the female voice*) to 6 (*sure it was spoken by the male voice*) in the second space beside each word. They were told to make a recognition and source judgment

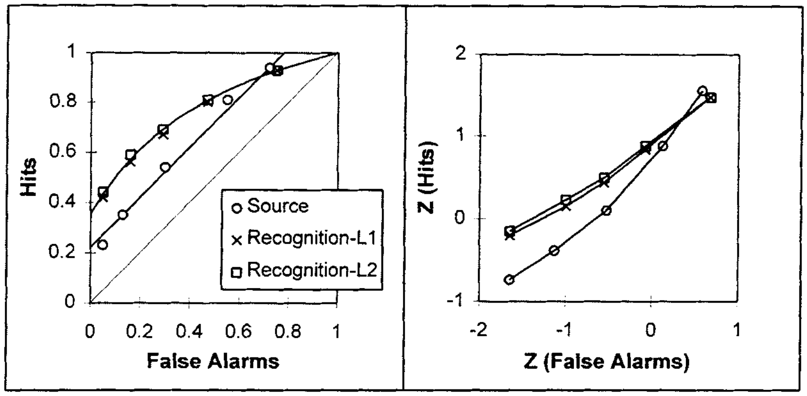

Figure 4. Recognition and source-memory receiver operating characteristics for Experiment 2, plotted in probability space and fit with the dual-process model (left panel) and plotted in *z*-space (right panel). Recognition performance is plotted separately for items that were studied in the first list (L1) and the second list (L2).

for every word. As in the previous experiment, participants were told to try to use the entire range of responses. Participants were told to work through the booklet 1 word at a time, making a recognition and source judgment for each word before going onto the next. The session took approximately 45 min to complete.

Results and Discussion

Receiver operating characteristics (ROCs). Recognition and source-memory ROCs for Experiment 2 are presented in Figure 4. The hit rate for the source task was defined as the probability of correctly accepting a word from List 1 as coming from List 1. The false-alarm rate was defined as the probability of incorrectly accepting a word from List 2 as coming from List 1. Because the recognition performance for the items from the two different sources was very similar, the recognition scores were collapsed across this variable before the analysis.

As in Experiment 1, the dual-process model was fit to the observed ROCs. An examination of Figure 4 shows that the model provided an accurate fit for the recognition function and a reasonable, although less than perfect, fit for the source function. Two parameters were used for the recognition function (R and d'), and one parameter (R) was used to fit the source ROC (see Table 1).

A close examination of Figure 4 shows that the source ROC did deviate slightly from the predicted function in the sense that the observed ROC exhibited a small inverted-U shape. However, the linearity analysis showed that the recognition ROC was curvilinear and that the source ROC did not deviate significantly from linearity. For the recognition ROC, there was a significant linear component, R^2 = .8987, $F(1, 3)$ = 26.60, *MSE* = 0.0068, and the quadratic equation fit the data significantly better than the linear function, R^2 = .9991, $F(1, 2)$ = 220.73, *MSE* = 0.0005. In contrast, for the source ROC, there was a significant linear component, R^2 = .9940, $F(1, 3)$ = 498.13, *MSE* = 0.0002, and the quadratic equation did not lead to a significant improvement, R^2 = .9993, $F(1, 2)$ = 14.64, *MSE* = 0.0004.

To examine the effects of averaging, ROCs were plotted for each participant and as a function of test position. For recognition, 21 of the 24 participants exhibited an inverted U-shaped curve similar to the average recognition curve, showing that the average recognition function was representative of most of the individual participants' ROCs. For the source ROC, however, 14 participants exhibited relatively linear ROCs, 2 participants exhibited noticeable U-shaped curves, and 8 participants exhibited noticeable inverted U-shaped curves. Thus, although most of the participants' source ROCs were linear, one third of the participants exhibited an ROC with a noticeable inverted-U shape. As in the previous experiment, the shapes of the ROCs were not found to be greatly influenced by test position.

Z-receiver operating characteristics (z-ROCs). In agreement with the previous experiment, the recognition-memory *z*-ROC was linear, and the source-memory function was U-shaped (see Figure 4). For recognition, there was a significant linear component, R^2 = .9874, $F(1, 3)$ = 234.82, *MSE* = 0.0137, and the quadratic component did not provide a significant improvement over the linear function, R^2 = .9987, $F(1, 2)$ = 18.02, *MSE* = 0.0006.[2] For source memory, there was a significant linear component, R^2 = .9766, $F(1, 3)$ = 125.38, *MSE* = 0.0254, and introducing the quadratic component provided a significant improvement in fit, R^2 = .9995, $F(1, 2)$ = 82.98, *MSE* = 0.0003. The slope and intercept values of the best fitting linear function for the recognition *z*-ROC were 0.71 and 0.92, respectively. The slope and intercept values of the best fitting linear function for the source *z*-ROC were 1.03 and 0.83, respectively.

[2] As described in the *Method* section, a second linearity analysis was conducted using a regression method that incorporated variation in both the *y*- and *x*-dimensions. Unlike the standard regression analysis, it suggested that the average recognition *z*-ROC in Experiment 2 was significantly U-shaped. This finding is consistent with the dual-process model and is problematic for the unequal-variance model. However, because the deviation was not found using the standard regression method, it is not discussed further.

In sum, as in Experiment 1, recognition and source memory led to different types of ROCs. The recognition ROC was curvilinear in probability space and linear in *z*-space. In contrast, the source ROC was linear in probability space and U-shaped in *z*-space. The recognition results are consistent with both the dual-process model and the unequal-variance model, but the U-shaped *z*-ROC observed in the source task is inconsistent with the unequal-variance model. The dual-process model provided a good fit for the recognition ROC and a reasonable fit for the source ROC. However, a careful examination of the average source ROC suggested that the function did exhibit a slight inverted-U shape. Although the degree of nonlinearity did not reach the level of significance, approximately one third of the participants did exhibit this type of source ROC.

Why did such a large proportion of participants in Experiment 2 exhibit a curved source ROC? One possibility is that it was due to measurement error or noise. In fact, Ratcliff et al. (1994) showed that noise could lead memory ROCs to exhibit a slightly exaggerated inverted-U shape. However, another possibility is that the slight curvilinearity arose because some of the participants used familiarity as a basis for source judgments. Note that unlike Experiment 1, in which items from the two sources were randomly intermixed during the study phase, in Experiment 2, items from the first source were presented earlier than items from the second source. Thus, the average familiarity of the items in the two lists may have differed for some participants, and they may have used this difference as a basis for discriminating between the items from the two lists. Although it is not clear whether familiarity played a role in the source judgments in this experiment, the contribution of familiarity to source-memory ROCs was further examined in the next two experiments.

Experiment 3

Experiment 3 was designed to further examine source ROCs in conditions in which familiarity-based source judgments were discouraged. The procedure was exactly the same as that used in Experiment 2 except that the first list of words was presented twice and the second list was presented only once. This design was based on a procedure used by Huppert and Piercy (1978), who found that amnesic patients had a particularly difficult time distinguishing between recently and frequently presented items. They argued that the amnesic patients were unable to use recollection to make recognition judgments and thus had to rely exclusively on assessments of familiarity. Because high levels of familiarity could be due to the item's being either frequently or recently presented, amnesic patients should have a difficult time discriminating between these two types of items.

The idea in the present experiment was to design the source discrimination task such that a high level of familiarity could be due to either frequency (i.e., an item presented twice in List 1) or recency (i.e., an item presented once in List 2) and thus to dissuade participants from using familiarity when making their source-memory discriminations. Of course, there may be differences in the average familiarity of the items from List 1 and List 2 (e.g., more recent items may be more or less familiar than older twice-presented items), but given there is no obvious source attribution that the participants can make about familiarity, they should be less likely to use it as a basis for source judgments. Thus, the source ROC was expected to be linear. Because recollection of the List 1 and List 2 items could differ, a two-parameter model was used to fit the source ROC (R_t, R_l). The recognition function was expected to be similar to those found in the previous experiments.

Method

Participants and materials. Twenty-four undergraduates participated in the experiment for credit in an introductory psychology course. The materials were the same as those used in Experiment 2.

Design and procedure. Participants were tested in four groups of 6. The study and test phases were the same as those used in Experiment 2 except that in the study phase, participants heard the first list two times in succession immediately followed by the second list, which was presented only once. The session took approximately 55 min to complete.

Results and Discussion

Receiver operating characteristics (ROCs). Recognition and source-memory ROCs for Experiment 3 are presented in Figure 5, along with the fits of the dual-process model. Examination of Figure 5 shows that the model provided an accurate account of the recognition and source ROCs (see Table 1 for parameter estimates).

As in the previous experiments, the recognition ROCs were curvilinear and asymmetrical, and the source-memory ROC was fit well by a linear function. For the average recognition ROC, there was a significant linear component, R^2 = .9813, $F(1, 3)$ = 157.67, MSE = 0.0009, and the quadratic equation fit the function significantly better than the linear equation, R^2 = .9993, $F(1, 2)$ = 52.91, MSE = 0.0003. For the source ROC, there was a significant linear component, R^2 = .9948, $F(1, 3)$ = 577.72, MSE = 0.0005, and the quadratic equation did not lead to a significant improvement over the linear equation, R^2 = .9987, $F(1, 2)$ = 6.02, MSE = 0.0006.

To examine the effects of averaging, ROCs were plotted for each participant and as a function of test position. The shapes of the recognition and source functions were found to be representative of the individual participants ROCs. For recognition, 2, 7, and 15 participants exhibited linear, U-shaped, and inverted U-shaped ROCs, respectively. For source recognition, 18, 2, and 4 participants exhibited linear, U-shaped, and inverted U-shaped ROCs, respectively. The shapes of the source and recognition ROCs were not found to be greatly influenced by test position.

Z-receiver operating characteristics (z-ROCs). As in the previous experiments, the average recognition *z*-ROC was relatively linear, and the source *z*-ROC exhibited a pronounced U shape (see Figure 5). However, unlike in the previous studies, the linearity analysis showed that both the recognition and source functions were significantly U-shaped. For recognition, there was a significant linear

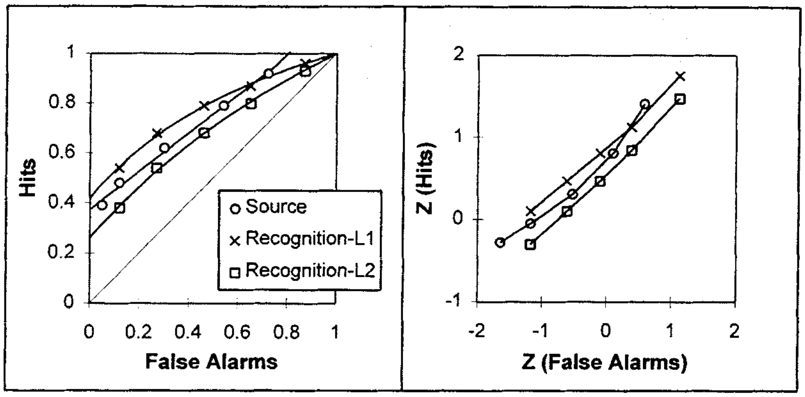

Figure 5. Recognition and source-memory receiver operating characteristics for Experiment 3, plotted in probability space and fit with the dual-process model (left panel) and plotted in *z*-space (right panel). Recognition performance is plotted separately for items that were studied in the first list (L1), which was presented twice, and the second list (L2), which was presented once.

component, R^2 = .9954, $F(1, 3)$ = 646.54, *MSE* = 0.0049, and the quadratic function provided a significant improvement over the linear function, R^2 = .9999, $F(1, 2)$ = 64.00, *MSE* = 0.0001. For source memory, there was a significant linear component, R^2 = .9678, $F(1, 3)$ = 90.26, *MSE* = 0.0345, and introducing the quadratic component provided a significant improvement in fit, R^2 = .9997, $F(1, 2)$ = 192.97, *MSE* = 0.0002. The slope and the intercept of the recognition *z*-ROC were 0.73 and 0.74, respectively. The slope and the intercept of the source *z*-ROC were 0.75 and 0.85, respectively.

In sum, as in the previous experiments, the recognition and source ROCs were quite different, and the predicted submodels of the general dual-process model provided an accurate fit for the recognition and source ROCs. The source ROC was linear in probability space and U-shaped in *z*-space. The recognition ROC was curvilinear in probability space, and although it was fit reasonably well by a linear function in *z*-space, it exhibited a consistent U shape. It is not clear why the recognition *z*-ROCs were significantly U-shaped in Experiment 3 but not in Experiments 1 and 2. Although recognition *z*-ROCs typically are linear, slightly U-shaped *z*-ROCs are occasionally observed in standard recognition tasks (e.g., Glanzer et al., 1999; Ratcliff et al., 1994; Yonelinas et al., 1996). The U-shaped recognition *z*-ROCs are consistent with the dual-process model, and they are problematic for the unequal-variance model.

Although the source ROCs in Experiments 1–3 did not deviate significantly from linearity, one third of the participants in Experiment 2 exhibited inverted U-shaped source ROCs. The slight curvilinearity observed in that experiment may have been due to the fact that familiarity was used to discriminate between the items from the two sources. However, the degree of curvilinearity observed was very small, and it may have been due to noise rather than to the use of familiarity. The next experiment was designed to test explicitly the notion that familiarity-based source-memory judgments would result in a curvilinear source ROC.

Experiment 4

If familiarity-based source judgments lead to curvilinear source ROCs, then it should be possible to increase the nonlinearity of the source ROC by creating conditions in which high levels of familiarity are clearly indicative of an item's source. Experiment 4 was similar to Experiment 2 except that only source memory was tested and there was a long delay introduced between the presentation of the two study lists. Participants were presented with the first list on Day 1 and the second list 5 days later. Immediately following the presentation of the second list, they were given a source-memory test for words presented in the two lists. The idea was that words from the second list should be much more familiar than those presented 5 days earlier, and this difference should be obvious to participants. Thus, participants should be willing to attribute an item's high level of familiarity to the occurrence of that item in the most recent list. Recollection should still be useful, but familiarity should also play an important role. Thus, the source ROC was expected to be curved. Whether the *z*-ROC would exhibit a significant U shape was not clear. If recollection and familiarity contributed in a manner similar to that seen in standard recognition conditions, then the expected U shape would be quite small. However, if the contribution of recollection was much greater than familiarity, then the *z*-ROC would exhibit a significant U shape like that seen in the three previous experiments. Because familiarity was expected to contribute to performance and because recollection of the List 1 and List 2 items could differ, a three-parameter model was used to fit the ROC (R_t, R_l, and d').

Method

The method was the same as that used in Experiment 2 except for the following changes. Forty-five students participated in the experiment, which served as a class demonstration in an introductory psychology course. Fourteen participants were excluded because they were not present during the presentation of one of the study lists. The analysis was conducted on the data from 24 participants who were randomly selected from the remaining students. The study lists were read aloud at a rate of approximately 3 s per item. There was a 5-day delay between the two study lists, and the participants were tested only for source memory. The source-memory test included the items from the two lists presented in a random order.

Results and Discussion

Receiver operating characteristics. The source-memory ROC for Experiment 4 is presented along with the fit of the dual-process model in Figure 6. List 2 was treated as the target list. An examination of Figure 6 shows that the dual-process model provided an accurate account of the source ROC. Three parameters were used to fit the ROC, representing the probability of recollecting the source of List 2 and List 1 items and the difference in familiarity between items from the two lists (see Table 1).

As expected, the source-memory ROC in this experiment was curvilinear. The analysis showed that there was a significant linear component, $R^2 = .9827$, $F(1, 3) = 170.13$, $MSE = 0.0026$, and the quadratic equation fit the observed data significantly better than the linear equation, $R^2 = .9998$, $F(1, 2) = 171.30$, $MSE = 0.0001$. An examination of individual participants' data showed that the average ROCs were representative of the participants' curves (5, 1, and 18 participants' ROCs were linear, U-shaped, and inverted U-shaped, respectively). Thus, as predicted, when familiarity-based source discrimination was made likely, the source-memory ROC exhibited a pronounced nonlinearity.

Z-receiver operating characteristics. Figure 6 presents the average source ROC plotted in *z*-space. As with the previous experiments, the source *z*-ROC was U-shaped. The *z*-ROC exhibited a significant linear component, $R^2 = .9702$, $F(1, 3) = 97.61$, $MSE = 0.0276$, and introducing the quadratic component provided a significant improvement in fit, $R^2 = .9997$, $F(1, 2) = 203.66$, $MSE = 0.0001$. The slope and the intercept of the source *z*-ROC were 0.70 and 0.87, respectively.

In sum, the results of Experiment 4 showed that when familiarity-based source discriminations were encouraged, the source ROC became curvilinear. The results are consistent with the predictions of the dual-process model. Moreover, as in all the previous experiments, the U-shaped *z*-ROC showed that the unequal-variance signal-detection model was not consistent with the source-memory data. The curvilinearity of the source ROC showed that recollection alone was not sufficient to account for performance and suggested that familiarity could be used to support source discriminations. Moreover, the three-parameter dual-process model that included recollection and familiarity was found to provide an accurate account for the source-memory ROC.

General Discussion

The results of Experiments 1–4 were consistent in showing that recognition and source memory dissociated in terms of the shape of their respective ROCs. Recognition ROCs were curvilinear in probability space, and they were generally linear in *z*-space. In contrast, source ROCs were generally linear in probability space and U-shaped in *z*-space. These results were in agreement with the predictions of the dual-process model, and the observed ROCs were fit well by the model's equations. In the recognition tests, in which participants were expected to rely on both recollection and familiarity, the ROCs were curved and asymmetrical. In contrast, in the source tests, in which participants were expected to rely primarily on recollection (i.e., Experiments 1–3), the ROCs were linear. Importantly, in Experiment 4, in which familiarity-based source discriminations were promoted by introducing a long delay between the presentation of the items from the two sources, the source ROC became curvilinear.

The recognition ROCs were similar to those seen in many previous studies in the sense that they were curvilinear and asymmetrical in probability space and linear in *z*-space (e.g., Donaldson & Murdock, 1968; Egan, 1958; Gehring et al., 1976; Glanzer & Adams, 1990; Murdock & Dufty, 1972; Ratcliff et al., 1992; Yonelinas, 1994). Note that there was a significant U-shaped recognition *z*-ROC in Experiment 3, and similar U-shaped recognition ROCs have been observed in other studies (e.g., Ratcliff et al., 1994; Yonelinas et al.,

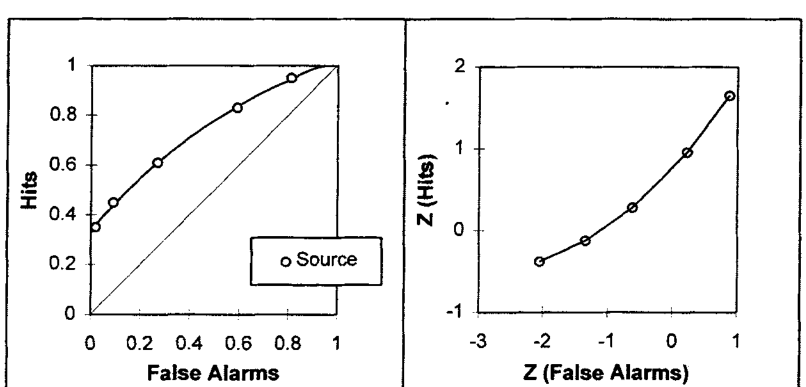

Figure 6. Source-memory receiver operating characteristics for Experiment 4, plotted in probability space and fit with the dual-process model (left panel) and plotted in *z*-space (right panel).

1996). These findings suggest that recollection can sometimes have a detectable effect on the curvilinearity of the recognition ROCs.

The source z-ROCs were significantly U-shaped in all four experiments, as expected if a threshold recollection process played a dominant role in performance. z-ROCs that exhibit a pronounced U shape are not common in memory studies, but they recently have been observed in tests of associative recognition in which participants were required to determine whether two items had previously been paired together (e.g., Yonelinas, 1997; Yonelinas, Kroll, Dobbins, & Soltani, in press). These results suggest that the retrieval processes that support associative and source-memory judgments are well described as threshold processes.

Beyond these general predictions, the dual-process model was found to provide an accurate fit for the observed recognition and source-memory ROCs in all four experiments (see Figures 3, 4, 5, and 6). In the case of recognition, the ROCs were accounted for by using one memory parameter for recollection (R_t) and one for familiarity (d'). In the case of source memory, the model was the same, except that an additional recollection parameter was required to account for the fact that participants could recollect the occurrence of items from two lists rather than just one. Although the full model required three free memory parameters (i.e., R_t, R_l, and d'), there were conditions in which fewer parameters were used. For example, in Experiments 1, 2, and 3, in which familiarity was not expected to contribute greatly to source discriminations, the contribution of familiarity was set to zero (i.e., $d' = 0$). Furthermore, in Experiments 1 and 2, in which the probability of recollecting items from the two sources was expected to be the same, the two recollection parameters were collapsed into a single parameter. Thus, in the simplest case, the source ROC was accounted for with a single memory parameter. However, in Experiment 4, in which source judgments were expected to rely on familiarity as well as recollection and the probability of recollecting items from the two sources differed, all three parameters were used.

The number of parameters required to account for the ROCs was predicted a priori; however, in Experiment 2, several of the participants' source ROCs exhibited an unexpected curvilinearity. One possible explanation is that these participants used familiarity to discriminate between the items from the two sources. The claim that the familiarity process could contribute to source-memory judgments and that this leads to curvilinear ROCs was tested in Experiment 4. The results of that study showed that when familiarity-based source discrimination was promoted by making familiarity clearly indicative of list membership, the source ROC exhibited a pronounced curvilinearity.

The present results join numerous previous studies in showing that recognition and source-memory performance can dissociate. However, the present experiments also showed that such a dissociation was easy to disrupt. In conditions in which familiarity was expected to contribute to source memory, the ROC exhibited a pronounced curvilinearity that was similar to that seen in the recognition ROCs. These results are important in showing that source-memory tasks do not always rely exclusively on recollection. As mentioned previously, the dissociations between these two tasks are such that it is tempting to think that there may be a "source-memory process" that is separate from those processes underlying recognition-memory performance. The present results do not support this claim; rather, they show that source-memory performance can be understood within the same dual-process framework that has proved to be useful in understanding recognition memory. In the present study, I tried to shift the focus away from memory tasks and toward memory processes. Such an approach has been strongly advocated by others (e.g., Jacoby, 1991; Johnson, 1983; Moscovitch, 1992). Building on these ideas, the approach taken in this article was to develop a formal model and to assess whether that model provided an accurate account of performance in different tasks.

Alternative Models

An alternative model that has proved to be very useful in accounting for recognition memory is the unequal-variance signal-detection model. This model provided a good account for most of the recognition data in these experiments; the finding that the recognition z-ROCs were often linear and exhibited a slope of less than 1.0 is consistent with the model. Note, however, that the recognition ROC in Experiment 3 was significantly U-shaped, which is inconsistent with the predictions of the model.

Signal-detection-based models also have been proposed to account for source-memory performance (e.g., Hoffman, 1997; Marsh & Bower, 1993). The present results lend some support to these theories in the sense that they show that familiarity can contribute to source-memory judgments. But the results also show that signal-detection theory in itself was not sufficient to account for source-memory performance. That is, the significantly U-shaped z-ROCs that were observed for source-memory judgments in every experiment showed that the model was inconsistent with the source-memory data. If, as the model assumes, the old- and new-item distributions are normally distributed, then the observed z-ROCs should have been linear.

Although the U-shaped z-ROCs do argue against the unequal-variance model, it is useful to directly contrast the fit of that model to that of the dual-process model. To do so, I fit both models to the average ROCs in each experiment by using a maximum-likelihood estimation method (Ashby, 1992) and calculated Akaike's (1974) information criterion (AIC). The AIC values cannot be statistically contrasted, but they do provide a badness-of-fit estimate that compensates for the number of free parameters in each model (see Takane & Shibayama, 1992). In this way, it is possible to contrast the unequal-variance model with submodels of the dual-process model that have fewer or more free parameters. The AIC values for each model are presented in Appendix B. For recognition memory, there was no consistent advantage for either model. They both provided very similar fits for the ROCs: The dual-process model provided a slightly smaller AIC in Experiment 2, and the reverse was observed in Experiments 1 and 3. In contrast, for the source-memory

ROCs, the dual-process model provided a better fit than the unequal-variance model in every experiment. Thus, the direct comparison of the two models led to similar conclusions as the earlier linearity analyses; the two models provided an equally good account of recognition, but the dual-process model provided a better account of the source-memory data.

The finding that the source ROCs are problematic for the unequal-variance signal-detection model suggests that other models that rely on similar assumptions are also in conflict with the data. For example, Anderson and Bower's (1974) recognition model and several global memory models—for example, TODAM (Murdock, 1982), the search of associative memory model of recall (Gillund & Shiffrin, 1984), and MINERVA 2 (Hintzman, 1986)—produce memory distributions that are approximately normal, and thus they produce curvilinear ROCs. The inability of the global memory models to account for the existing ROC results may lie in the assumption made by these models that recognition judgments are based solely on the assessment of a single familiarity process. However, all of these models do possess recall-like search mechanisms that could be incorporated into recognition (for a discussion of this possibility, see Clark & Gronlund, 1996). One model that may be particularly well suited to the ROC data is TODAM. This model assumes that items that are represented as vectors are encoded in a distributed manner across a common memory vector. The memory strength (or familiarity) of an item is determined by taking the dot product of the item and memory vector. Studied items tend to lead to higher levels of familiarity than do new items. The model predicts normal familiarity distributions; however, unlike the other global memory models, it produces old and new familiarity distributions that are approximately equal in variance. Thus, it would be in agreement with the dual-process model with respect to the familiarity component. If the recall mechanism were allowed to contribute to recognition performance, it might bring the model in line with the observed ROCs. Moreover, recent simulations using the TODAM model (Kahana, 1998) have shown that item familiarity may be independent of the recall process; thus, the model is in general agreement with the assumption underlying the dual-process model that recollection and familiarity are independent. However, it is not known if TODAM's recall mechanism would behave like recollection; thus, it is not yet clear whether such a model would provide a viable computational realization of the dual-process model. One reason for suspecting that it might not is that recollection in a recognition task has been found to be functionally dissociable from free-recall performance (Dobbins, Kroll, Yonelinas, & Liu, 1998).

An alternative approach that has some similarities with the dual-process model is the source-monitoring framework proposed by Johnson and colleagues (for a review, see Johnson et al., 1993). By this framework, there are numerous types of information that participants may use for making judgments about the source of an item and many processes that may be recruited in the service of such judgments. The model does not make explicit assumptions about the underlying nature of recollection and familiarity; thus, it does not predict the linear and curvilinear source and recognition ROCs that were observed in the present study. However, the two approaches are similar in the sense that neither approach treats recognition and source-memory tasks as reflecting two fundamentally different processes. Rather, they view the two tasks as relying on the same set of underlying processes.

A model that is sometimes used in studies of source memory that does make explicit assumptions about the nature of recognition and source ROCs is the multinomial model of Batchelder and Riefer (1990). The model assumes that both recognition performance and source performance are well described by threshold theory. Thus, the model predicts that both recognition and source ROCs should be linear. The present results showed that both recognition and source ROCs could be curvilinear; thus, the model is not consistent with the ROC data (for similar criticisms of threshold models, also see Kinchla, 1994; Murdock, 1974).

A theoretical approach that appears to be consistent with the present dual-process model is the neural network model of O'Reilly, Norman, and McClelland (1997). The model posits that recollection is subserved by structures within the hippocampal region (e.g., CA1, CA3, dentate gyrus) and that familiarity is subserved by structures outside of this region. Importantly, the hippocampal component behaves like a threshold process, and thus it is consistent with the results of the present study. Moreover, the model accounts for several aspects of the amnesia literature as well as some of the recognition data from the process dissociation procedure (e.g., Yonelinas & Jacoby, 1994). Such a modeling approach may provide a critical link between the behaviorally motivated dual-process model and neurobiologically based models.

Evaluating the Assumptions of the Dual-Process Model

These results join a growing body of research supporting the dual-process signal-detection model. Most important, the model correctly predicted linear source ROCs that were U-shaped in *z*-space. Given that such a prediction conflicts with a large body of recognition studies reporting curvilinear memory ROCs and that it conflicts with the predictions of a model that has been widely accepted in the study of memory (i.e., the unequal-variance model), these novel findings provide strong support for the dual-process model.

In addition, the model provided a way of integrating literatures that often are treated as quite separate. For example, the present results showed that it was possible to account for source-memory performance using the same framework that has been useful in studies of standard recognition. The model also has been useful in integrating the results from item and associative recognition (e.g., Yonelinas, 1997) and from studies using the process dissociation (Yonelinas, 1994) and remember–know procedures (e.g., Yonelinas & Jacoby, 1995).

One advantage of working with a simple quantitative model is that it is based on a relatively small number of assumptions that can be explicitly tested. That the model is found to accurately fit the observed recognition and source-memory ROCs provides indirect support for the model's assumptions. However, it is also useful to look for situations that provide tests of individual assumptions. One critical assumption is that recollection is a threshold retrieval process. A test of this assumption is to look for cases in which performance relies primarily on recollection and to determine if linear ROCs are obtained. As expected, linear ROCs were observed in the present study, and they also have been observed in other conditions in which performance is expected to heavily rely on recollection (e.g., associative recognition).

A second critical assumption is that familiarity reflects an equal-variance signal-detection process. There is no a priori reason why the familiarity distributions must be Gaussian or that the old- and new-item distributions must be equal in variance. A way to directly test these assumptions is to examine recognition performance in individuals who exhibit severe deficits in recollection to determine if familiarity is well described as a signal-detection process. To do this, Yonelinas et al. (1998) examined the ROCs of amnesic patients and found that, in contrast to healthy control participants, the amnesic patients exhibited symmetrical ROCs (e.g., see Figure 2B) like those expected if performance were based on an equal-variance signal-detection process. Additional support for the threshold and signal-detection assumptions comes from studies using the process dissociation and remember–know procedures to estimate familiarity; these studies have shown that familiarity and recollection are well described as equal-variance signal-detection and threshold processes, respectively (e.g., Yonelinas, 1994; Yonelinas & Jacoby, 1995; but see Ratcliff, Van Zandt, & McKoon, 1995).

A third critical assumption is that recollection and familiarity are independent processes. This assumption is supported by the finding that recollection and familiarity are functionally dissociable (for a review, see Jacoby, Yonelinas, & Jennings, 1997) and by event-related potential studies showing that the two processes are associated with qualitatively distinct electrophysiological components (Düzel et al., 1997).

Although the model's assumptions are well supported, there are a number of critical limitations to the model. Most obvious is that the model is far too simple; that recognition-memory performance could be accounted for with two or three free memory parameters is extremely unlikely. There clearly will be cases in which additional or alternative assumptions will be required. Second, there were cases in the present experiments, and in previous studies (Glanzer et al., 1999; Ratcliff et al., 1995; Yonelinas, 1999), in which the model deviated slightly from the observed ROC points. Although these deviations tended to be quite small (i.e., in the worst cases, the model predicted points that were between .01 and .02 from the observed ROC points), a further examination of these deviations may be important in developing future models. Most important, however, is that the model does not specify how memories are represented or how these processes are neurally instantiated. Although it is broadly consistent with some neuroanatomical models of the medial temporal lobes (e.g., Aggleton & Brown, in press; O'Reilly et al., 1997), careful consideration of known biological constraints will be essential in the development of future memory models. However, what is clear is that the model does provide a very simple and powerful tool for understanding memory performance in recognition and source-memory tasks, and it does point to a fundamental distinction between two different types of recognition retrieval processes.

Future Tests of the Dual-Process Model

In the present experiments, familiarity-based source discrimination was found to increase the curvilinearity of the source ROCs. However, there are other factors that may influence the curvilinearity of the source functions. For example, the manner in which the item and source information are integrated may influence whether familiarity contributes to source judgments. As previously discussed, tests of associative recognition tend to lead to linear ROCs; however, under conditions in which the items in a pair form a well-integrated whole, curvilinear ROCs can be observed (Yonelinas, 1997; Yonelinas et al., in press). Similarly, in conditions in which the item and the source information are more closely integrated, such as may be the case when two individuals are holding a conversation, familiarity may support source judgments. Curvilinear source ROCs also may be observed when study episodes are very complex and participants are able to retrieve numerous different types of information about the study events. In the present experiments, the study events were relatively impoverished; items were presented once or twice for a few seconds each. In these conditions, participants may not have recollected many different aspects of the study event. However, if participants are able to recollect numerous aspects of the study event that link the item to a specific source, then even if recollection is a threshold retrieval process, it may begin to behave in a more continuous manner. Similarly, curvilinear source ROCs also may arise when participants retrieve information that is less than a perfect predictor of source. For example, I may recollect that a comment was made by someone I knew very well, and this may help me narrow the possible sources of that information, thus slightly increasing my chances of correctly determining the source.

Future studies that examine the effects of event complexity and probabilistic source information on recognition and source ROCs will be useful in further assessing the usefulness of the threshold and signal-detection assumptions underlying the dual-process model. Under more complex study and test conditions, it may be appropriate to describe both familiarity and recollection as signal-detection processes (see Macmillan & Creelman, 1991, for a description of multidimensional signal-detection theories). Alternatively, recollection may be better described as a threshold process that produces discrete step functions rather than rectangular or Gaussian distributions.

Conclusion

A dual-process signal-detection model was described in which familiarity (a signal-detection process) and recollection (a threshold retrieval process) independently contribute to memory performance. The model was generalized to account for source-memory performance, and it was tested in four experiments examining recognition and source-memory ROCs. In agreement with the model's predictions, the recognition ROCs were curvilinear and asymmetrical, and the source ROCs were linear except when familiarity contributed to source discrimination. Moreover, the model provided an accurate fit for both recognition and source-memory ROCs, and the ROC data were found to be inconsistent with several alternative models, including the unequal-variance signal-detection model. The results show that the dual-process framework is useful in understanding both recognition and source-memory performance and suggests that familiarity and recollection are well described as signal-detection and threshold processes, respectively.

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(Appendixes follow)

Appendix A

Counts per Confidence Category

Response category	1	2	3	4	5	6
Experiment 1						
Source memory						
Lure (left)	563	121	161	157	105	93
Target (right)	83	103	143	139	155	577
Recognition memory						
Lure (new)	845	528	383	279	199	156
Target (left)	74	71	88	117	106	744
Target (right)	78	86	68	100	126	742
Experiment 2						
Source memory						
New	78	244	883	550	128	37
Lure (List 2)	537	319	492	328	144	100
Target (List 1)	107	255	522	356	229	451
Recognition memory						
Lure (new)	471	547	345	256	200	101
Target (List 2)	139	230	223	204	274	850
Target (List 1)	142	242	246	219	261	810

Response category	1	2	3	4	5	6
Experiment 3						
Source memory						
New	113	393	717	497	131	69
Lure (List 2)	547	343	447	355	155	577
Target (List 1)	149	247	327	280	170	747
Recognition memory						
Lure (new)	249	420	377	356	294	224
Target (List 2)	140	242	239	253	307	739
Target (List 1)	69	185	156	202	273	1035
Experiment 4						
Source memory						
Lure (List 1)	357	426	622	348	126	41
Target (List 1)	94	238	411	321	191	655

Appendix B

Akaike's (1974) Information Criterion (AIC) Values Associated With the Unequal-Variance and Dual-Process Signal-Detection Models for the Average Recognition and Source-Memory Receiver Operating Characteristics in Experiments 1–4

	Recognition task		Source-memory task	
Experiment	Unequal-variance model	Dual-process model	Unequal-variance model	Dual-process model
1	13,950 (d', V_o)	13,957 (d', R_t)	7,370 (d', V_o)	7,344 (R)
2	18,624 (d', V_o)	18,615 (d', R_t)	12,916 (d', V_o)	12,885 (R)
3	18,576 (d', V_o)	18,578 (d', R_t)	12,675 (d', V_o)	12,624 (R_t, R_l)
4			12,431 (d', V_o)	12,368 (d', R_t, R_l)

Note. Lower AIC values represent better fits. The free parameters for each model are presented in parentheses. d' refers to the distance between the old- and new-item distributions in the unequal-variance model and the dual-process model. V_o refers to the variance of the old-item distribution in the unequal-variance signal-detection model, given the variance of the new-item distribution is assumed to be 1.0. R_t and R_l refer to the probability of recollecting target and lure items, respectively, in the dual-process model.

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