

COMMENTS

Moving Beyond Pure Signal-Detection Models: Comment on Wixted (2007)

Colleen M. Parks and Andrew P. Yonelinas
University of California, Davis

The dual-process signal-detection (DPSD) model assumes that recognition memory is based on recollection of qualitative information or on a signal-detection-based familiarity process. The model has proven useful for understanding results from a wide range of memory research, including behavioral, neuropsychological, electrophysiological, and neuroimaging studies. However, a number of concerns have been raised about the model over the years, and it has been suggested that an unequal-variance signal-detection (UVSD) model that incorporates separate recollection and familiarity processes (J. T. Wixted, 2007) may provide an equally good, or even better, account of the data. In this article, the authors show that the results of studies that differentiate these models support the predictions of the DPSD model and indicate that recognition does not reflect the summing of 2 signal-detection processes, as the new UVSD model assumes. In addition, the assumptions of the DPSD model are clarified in order to address some of the common misconceptions about the model. Although important challenges remain, hybrid models such as this provide a more useful framework within which to understand human memory than do pure signal-detection models.

Keywords: recognition memory, recollection, familiarity, dual-process signal detection, unequal-variance signal detection

The examination of recognition memory receiver-operating characteristics (ROCs) has played a critical role in shaping understanding of human memory. In fact, the ROC studies conducted in the early 1960s are largely responsible for the dominance of signal-detection-based theories in the memory literature today. Those early studies revealed two major discoveries that provided important constraints on memory theory. First, they revealed that recognition ROCs were curvilinear, a finding that supports the predictions of signal-detection theory and disconfirms those of several threshold theories that predict linear ROCs (see Murdock, 1974). Second, although ROCs were curved, they were invariably asymmetric (e.g., Ratcliff, Sheu, & Gronlund, 1992), therefore ruling against the simplest type of signal-detection theory, which predicts symmetrical ROCs (i.e., the equal-variance signal-detection model).

Although many models have been introduced to account for recognition ROCs, the two models that have been examined most closely in recent years are the dual-process signal-detection model (DPSD; e.g., Yonelinas, 1994, 2001b) and the

unequal-variance signal-detection model (UVSD; e.g., Glanzer, Kim, Hilford, & Adams, 1999; Wixted, 2007). The DPSD model integrates signal-detection theory and threshold theory within a dual-process framework of recognition memory (e.g., Atkinson & Juola, 1974; Jacoby, 1991; Mandler, 1980). The model has several important assumptions: First, recognition decisions are assumed to be based on two qualitatively different processes, recollection and familiarity. Second, familiarity is assumed to be well described by a signal-detection process such as that underlying the equal-variance signal-detection model¹ (see Figure 1A) and thus is indexed as the difference in strength between studied and new items (i.e., d'). These first two assumptions tend not to garner much attention anymore—that is, there is relatively widespread agreement that recognition memory involves recollection and familiarity and that familiarity is well described as a signal-detection process of some sort (e.g.,

¹ The assumption of equal variance does not entail that each item has the same amount of strength added to it at study, but it does entail that on average, the variability in memory strength is comparable for the old and new items. This assumption could of course be relaxed (e.g., see Healy et al., 2005, for such a modification). For example, if familiarity had an upper limit, the old-item variance might be less than the new-item variance, or if there was some effective lower limit on familiarity, new items may have less variability. Nonetheless, the equal-variance assumption is the simplest starting assumption and has been supported in studies designed expressly to test it (Yonelinas, 2001a, 2001b). Recently, other models have adopted it in various forms as well (e.g., DeCarlo, 2002, 2003; Kelley & Wixted, 2001; Sherman et al., 2003).

Colleen M. Parks and Andrew P. Yonelinas, Department of Psychology, University of California, Davis.

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Correspondence concerning this article should be addressed to Colleen M. Parks, Department of Psychology, University of California, One Shields Avenue, Davis, CA 95616. E-mail: cmparks@ucdavis.edu

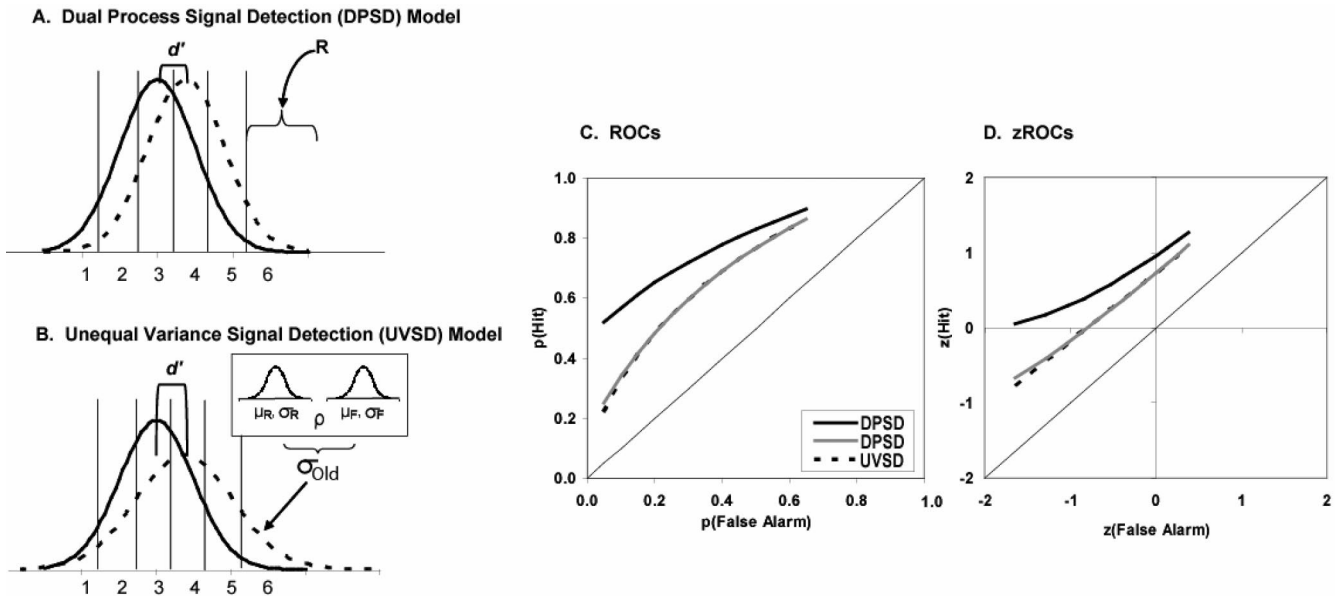


Figure 1. A: The dual-process signal-detection (DPSD) model with the new distribution represented by the solid line and the old distribution represented by the broken line. R represents recollection, which is assumed to lead to high-confidence responses relative to familiarity. B: The unequal-variance signal-detection (UVSD) model with the new distribution represented by the solid line and the old distribution represented by the broken line. Discriminability (d') represents the distance between the means of the old and new distributions. σ_{Old} represents the variance of the old-item distribution relative to the new-item distribution. The distributions in the inset represent the recollection and familiarity distributions proposed by Wixted (2007) to make up the old distribution. μ_R and σ_R are the mean and variance of the recollection distribution, respectively; μ_F and σ_F are the mean and variance of the familiarity distribution, respectively. ρ represents the correlation between recollection and familiarity. In Wixted's proposed model, the mean of the old distribution is equal to the sum of the means of the new, recollection, and familiarity distributions, and the variance of the old distribution is equal to $\sigma_{New}^2 + (\sigma_R^2 + \sigma_F^2 + 2\rho\sigma_R\sigma_F)$. C: Receiver-operating characteristics (ROCs) predicted by the models. D: z-transformed ROCs predicted by the models. Note that the black and gray DPSD lines reflect different levels of recollection and familiarity. The black function reflects a greater relative contribution of recollection than familiarity, and the gray function reflects a greater relative contribution of familiarity.

Diana, Reder, Arndt, & Park, 2006; Malmberg & Xu, 2006; Wixted, 2007; Yonelinas, 2002).

However, the third assumption—that recollection can be well described as a threshold process—has been met with a good deal of criticism and misunderstanding. We have described recollection as a threshold process because it can succeed in some cases but can fail in others. That is, participants can sometimes recollect qualitative information about a previous study event (e.g., when or where it occurred), but in other cases they are unable to recollect that information. Thus, as in free recall, recollection can be measured as a simple probability (R , or the probability that an item is recollected). Although the types and amount of information that participants can recollect will differ, recollection will sometimes fail or fall below the recollective threshold.

The threshold assumption has been misinterpreted as suggesting that recollection cannot be graded or that all recollected items must be equally strong. The reason for the misunderstanding may be due in part to a phrase from Yonelinas (1994) that Wixted (2007) quoted, in which a threshold process is described

as being “all-or-none”—a phrase intended to mean that the process can succeed or fail. However, since the original article was published, we have been careful to avoid using the term *all-or-none* because it is consistently (mis)interpreted as meaning that *everything* or *nothing* about an item is recollected or that recollection results in one homogeneous state (such that all recollected details are equal in strength). In an attempt to clarify the meaning of the threshold assumption, Yonelinas, Dobbins, Szymanski, Dhaliwal, and King (1996) wrote

It has recently been argued that when one assumes that recollection is a threshold process that this entails that recollection is all-or-none in the sense that either all of the information about a study event is recollected or none of the information is recollected (Dodson & Johnson, 1996). However, this is not a requirement of threshold theories, and the dual-process model does not assume that participants either recollect all the study information or none of the study information . . . the term “threshold” refers to the fact that an item will only be recognized if its memory strength exceeds a specific threshold; items falling above the threshold are recognized and those falling below the threshold are not. (p. 439)

Thus, the model assumes that recollection can be graded. In fact, we have demonstrated exactly that in experiments showing that people can recollect different aspects of a studied item with different probabilities (Yonelinas & Jacoby, 1996; Toth & Parks, 2006).² Those studies showed not only that different amounts of information can be recollected about an item but also that recollected information can vary in how diagnostic it is of source, including study-list membership.

Although we assume that recollection can vary, we have remained agnostic about the precise shape of the recollection distribution. That is, describing recollection as a threshold process means that it is measured as a probability (i.e., the proportion of items that exceed the threshold) and that it does not specify exactly how recollection strength values are distributed (see also Macmillan & Creelman, 2005). The recollection strength distribution that exceeds the threshold could take on any number of shapes, ranging from rectangular to Gaussian (see Sherman, Atri, Hasselmo, Stern, & Howard, 2003, for a Gaussian example). However, there is very little empirical evidence that tells us what the shape of the recollection distribution is, and as we show below, the evidence to date has shown that measuring recollection as a simple probability actually works quite well.

An important aspect of the DPSD model that is related to the threshold assumption is the expectation that performance will be based on recollection when it is successful and on familiarity when recollection fails (i.e., the item falls below the recollection threshold).³ The logic underlying this assumption is that because recollection provides qualitative information linking the test item to a prior event, whereas familiarity provides only quantitative strength information, recollection will generally provide the best evidence of prior occurrence. This means that although familiarity strength should lead to a wide range of recognition confidence responses (e.g., from 1 = *sure new* to 6 = *sure old*), it should not, at least under standard conditions, afford higher levels of recognition confidence than does recollection. In principle, participants could spread recollected items across the 5 and 6 levels of confidence as long as familiarity-based responses were limited to the 1–5 range. However, as described below, under standard conditions recollection appears to be associated primarily with 6 responses.

The DPSD model accounts for the basic recognition ROC findings—curvilinear and asymmetrical ROCs—in the following manner. Because the familiarity process is based on Gaussian distributions, the model predicts recognition ROCs that are curved. By itself, familiarity produces symmetrical ROCs because the old and new distributions are assumed to have the same shape (i.e., the distributions have equal variances). However, recollection is expected to increase the hit rate, which will effectively push the ROC up, leading the ROC to be asymmetrical, as is typically observed in item recognition.

The traditional UVSD model (see Figure 1B) takes a different approach to explaining recognition memory ROCs. Like the initial equal-variance signal-detection model, it assumes that memory decisions are based on a single memory strength assessment, with the old and new item strength values forming Gaussian distributions such that the studied items are stronger on average than the new items (indexed as d'). The UVSD model, however, incorporates an additional parameter that reflects the variance of the old item distribution relative to the new item distribution (σ_{old}). The Gaussian distributions lead the model to accurately predict item ROCs that are curvilinear, and the

variance parameter allows the model to account for ROCs that are asymmetrical. If the old items are associated with more variance than the new items ($\sigma_{old} > 1$), then the ROCs will be pushed up, as seen in item recognition, whereas if the old item variance is less than the new item variance ($\sigma_{old} < 1$), the ROCs will be asymmetrical in the other direction. This latter possibility is never really observed in item recognition memory studies but is at least theoretically possible according to the model.

The UVSD model is often interpreted as a single-process model in the sense that the strength dimension is assumed to reflect the results of a single underlying memory strength process (e.g., Donaldson, 1996; Dunn, 2004; Heathcote, 2003; Hirshman & Master, 1997). However, there is now considerable evidence from a wide variety of recognition paradigms indicating that such single-process models are unable to account for recognition (see Diana et al., 2006; Wixted, 2007; Yonelinas, 2002). To overcome this problem, Wixted (2007) has suggested that the strength measure of the UVSD model may reflect a combination of multiple memory signals (for a similar suggestion, see Johnson, Hashtroudi, & Lindsay, 1993). More specifically, Wixted has argued that the strength axis reflects the sum of recollection and familiarity, each of which are also described as UVSD models (see Figure 1B). That is, familiarity has a strength parameter (d') and variance ratio parameter (σ_F), and recollection also has a strength parameter (d') and variance ratio parameter (σ_R). The recollection and familiarity strengths are summed, and recognition responses are made on the basis of the overall, or summed, strength. We view Wixted's modification of the UVSD model to be an important advance. Because the model now incorporates recollection and familiarity processes, it can theoretically account for the many behavioral and neural dissociations that have been observed in the recognition literature and that have been taken as evidence against single-process models.

Contrasting the ROC Predictions of the DPSD and UVSD Models

The modified UVSD model is in many ways consistent with the DPSD model, but there is an important difference. The UVSD model assumes that the recollection and familiarity strengths are always summed together before a participant makes a recognition response. Thus, for every item, a recollection strength value and a familiarity strength value coming from Gaussian strength distribu-

² As evidence against the all-or-none assumption, Wixted (2007) referred to several other studies showing comparable effects (e.g., Dodson, Holland, & Shimamura, 1998; Gruppuso, Lindsay, & Kelley, 1997; Simons, Dodson, Bell, & Schacter, 2004). Although these results are problematic for some interpretations of the term *all-or-none*, they are entirely consistent with the threshold assumption underlying the DPSD model.

³ This is one of Wixted's (2007; see also Rotello et al., 2005) main criticisms of the DPSD model and is what he referred to as the *process-purity* assumption. The term *process pure* typically refers to the practice of treating performance on a memory task as a pure measure of some underlying form of memory, such as using indirect tests as measures of implicit memory (e.g., see Jacoby, 1991). However, Wixted (2007) used the term *process pure* in a very different way, such that it refers to the assumption that recollection will be sufficient to support a recognition decision when it is successful and relevant to the decision.

tions are added together, and it is this summed information that serves as a basis for recognition responses. That is, participants cannot selectively base their responses on recollection or familiarity, even if they are instructed to do so as in the remember-know (RK) procedure. Instead, recollection and familiarity signals are combined prior to any recognition decision.

In contrast, the DPSD model assumes that the threshold recollection process can serve as a basis for recognition independently of familiarity. That is, if a participant can recollect some information about a study item, he or she can use that as a basis for responding, independently of the familiarity strength of the item. When recollection is not successful though, performance is based on familiarity. The resulting old-item distribution is therefore a mixture of Gaussian familiarity and threshold recollective strengths, but these strength values are not added together for each item. It is important to keep in mind that the terms *summing* and *mixing* have very different implications here. Summing means that for every item, recollection and familiarity strengths are added together, and if that strength exceeds the criterion, the item will be accepted. Mixing means that decisions about some items are made on the basis of the Gaussian familiarity distribution and decisions about other items are made on the basis of the threshold recollection distribution, and therefore the resulting old-item distribution reflects a mixture of the recollection and familiarity distributions.

Although this difference may seem fairly subtle, the two models can make very different predictions about the shape of recognition memory ROCs, and as we show next, the empirical results support the predictions of the DPSD model over those of the UVSD model. If the UVSD model is correct and the Gaussian recollection and familiarity strengths are summed together, then the resulting strength distribution must also be Gaussian. This point is not always obvious given the wide variety of shapes and strengths that Gaussian distributions can take on; nonetheless, the resulting summed distribution will always be Gaussian no matter how different the distributions of recollection and familiarity are in strength and variance. As Wixted (2007) pointed out, this means that his new model effectively collapses into the traditional UVSD model with respect to predictions regarding ROC shape. The standard test of the Gaussian assumption underlying this model is to take the z score of each ROC point and plot a z -ROC (e.g., Ratcliff et al., 1992). If the Gaussian assumption is correct, then the z -ROC will be linear (see Figure 1B), whereas significant deviations from linearity indicate violations of the assumption.

In contrast, according to the DPSD model, recollection and familiarity strengths are not summed together but operate independently of one another. This means that the effective old-item distribution is a mixture of the recollection distribution and the Gaussian familiarity distribution, and thus it will not be Gaussian. As Figure 1A shows, the recollection process essentially adds items to the right side of the Gaussian familiarity distribution, making the effective old-item distribution (which is not shown in the figure) asymmetrical. This has the effect of making the ROCs slightly flatter in probability space and U shaped in z space (see Figure 1).

ROCs From Item Recognition Are Generally Linear in z Space; Thus, They Are Consistent With Both Models

In standard item recognition tasks, in which the contributions of recollection and familiarity are usually comparable, the U shape

predicted by the DPSD model is extremely subtle, and thus the z -ROCs are not expected to deviate noticeably from linear (e.g., Yonelinas, 1999b). In fact, as Figure 1 shows, the DPSD model and the UVSD model can produce ROCs that are virtually indistinguishable. As a result, item recognition ROCs (which are generally linear in z space) are fit quite well by both the DPSD and the UVSD models.⁴

However, the differences between the models are more apparent in cases in which recollection is expected to play a larger role in performance than is familiarity. As recollection increases, the DPSD model predicts that the z -ROC will become more U shaped. However, this influence can be countered by high levels of familiarity, which has the opposite effect on the z -ROCs—that is, the greater the contribution of familiarity, the more linear the z -ROCs will be. Thus, the U shape of the z -ROCs should be most obvious when the contribution of recollection is relatively high and the contribution of familiarity is relatively low.

In contrast, different relative contributions of recollection and familiarity have no effect on the shape of the z -ROC under the UVSD model. Instead, the UVSD model assumes that the effective old-item distribution (i.e., the sum of recollection and familiarity) is Gaussian, as is the new distribution. Because both distributions are Gaussian, the model necessarily predicts curvilinear ROCs and linear z -ROCs, regardless of the levels of recollection and familiarity.

So how can these Gaussian (UVSD) and non-Gaussian (DPSD) assumptions be tested? Because the models predict such similar ROCs and z -ROCs in item recognition, it is necessary to examine data from recognition tasks that call for a relatively heavy reliance on recollection. Thus, relational recognition tasks, including source, associative, and plurality-reversed recognition tests, provide a perfect arena for pitting these two models against one another because they call for the retrieval of some specific detail about a test item (e.g., “What list was it in?” “What was it paired with?” “Was it singular or plural?”). Familiarity is still expected to contribute to performance in such tests, a point we discuss in more detail below, but will generally not be as diagnostic in relational recognition as it is in item recognition tests, in which old items have been studied and new items have not. The expectation of disproportionate contributions of recollection and familiarity to these tests leads the two models in question to make very different predictions about ROC and z -ROC shape. As suggested above, the DPSD model predicts that the ROCs will be flatter than those

⁴ Wixted (2007) described several item recognition studies and concluded that “most results show that the UVSD model far outperforms the DPSD model” (p. 156), but these conclusions simply are not supported by the empirical results. For example, of the studies that have directly contrasted the ROC fits of the two models, two have indicated a significant advantage for the DPSD model (Howard, Bessette-Symons, Zhang, & Hoyer, 2006; Yonelinas et al., 1996), three have reported an advantage for the UVSD model (Dougal & Rotello, in press; Healy et al., 2005; Rotello, Macmillan, Hicks, & Hautus, in press), and three have found that the two models provided comparable accounts (Kroll, Yonelinas, Dobbins, & Frederick, 2002; Prull, Dawes, Martin, Rosenberg, & Light, 2006; Yonelinas, 1999a). In addition, Heathcote (2003) reported an advantage for the UVSD model but found that in most cases the recognition ROCs exhibited an inverted U shape in z space—a result that is problematic for both the DPSD and UVSD models. Thus, the item recognition ROC literature does not provide definitive evidence in favor of either of these models.

typically seen in item recognition and that the z -ROCs will be noticeably U shaped. The UVSD model predicts that relational ROCs will be the same as item ROCs—curvilinear in probability space and linear in z space.

ROCs From Relational Recognition Tests Are Generally U Shaped in z Space; Thus, They Provide Strong Support of the DPSD Model Over the UVSD Model

When the prediction of U-shaped z -ROCs was first tested (Yonelinas, 1997), the existing item ROC literature was unanimous in supporting the Gaussian assumption (i.e., prior to this, item z -ROCs were almost always found to be linear). For this reason, when U-shaped z -ROCs were discovered in tests of associative recognition (Yonelinas, 1997), it was taken as rather compelling support for the DPSD model. The U-shaped z -ROCs were subsequently confirmed in tests of source memory (Yonelinas, 1999a), then in tests of plurality recognition (Rotello, Macmillan, & Van Tassel, 2000), both of which were expected to rely more on recollection than were item recognition tests. These U-shaped z -ROCs have now been reported by numerous labs using a wide variety of materials and test procedures (e.g., Arndt & Reder, 2002; DeCarlo, 2003; Glanzer, Hilford, & Kim, 2004; Healy, Light, & Chung, 2005; Hilford, Glanzer, Kim, & DeCarlo, 2002; Kelley & Wixted, 2001; Rotello et al., 2000; Slotnick, Klein, Dodson, & Shimamura, 2000; Slotnick & Dodson, 2005; Yonelinas, 1997, 1999a; Yonelinas, Kroll, Dobbins, & Soltani, 1999). To illustrate the consistency of these effects, Figure 2 presents the quadratic term of z -ROCs for 59 conditions from 17 studies of source, associative, and plurality-reversed recognition tests as a function of the linear z intercept (i.e., a rough index of overall performance). A positive quadratic term indicates that the z -ROC was U shaped. As shown, a vast majority of z -ROCs in source, associative, and plurality-reversed recognition are U shaped. Moreover, in the majority of these individual experiments, this nonlinearity was statistically reliable.

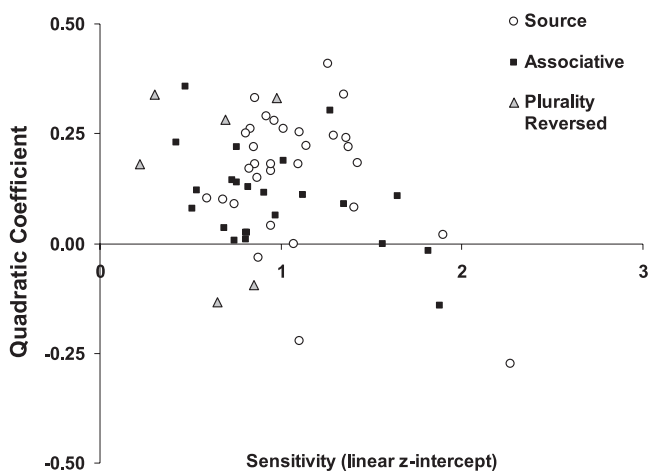


Figure 2. Quadratic coefficients plotted as a function of sensitivity in experiments examining relational recognition receiver-operating characteristics (ROCs). Positive values indicate cases in which the z -transformed ROC exhibited a U shape. In almost all cases, the relational ROCs were U shaped in z space.

Thus, there is now ample evidence that the z -ROCs in relational recognition studies are U shaped. This directly conflicts with the Gaussian assumption underlying the UVSD model and was predicted a priori by the DPSD model. Note that one potential response from pure signal-detection theorists is the argument that these results are anomalous or reflect the use of unusual test methods or study conditions (Glanzer et al., 1999; Wixted, 2007). However, the consistency of these effects now reported across a range of test procedures argues against such a position. Another possible approach is to argue that relational recognition data are irrelevant to understanding item recognition and that as long as one focuses only on item recognition, the UVSD model is perfectly adequate. For example, one could adopt the UVSD model for item recognition to account for the linear z -ROCs but adopt another model to account for relational recognition and the U-shaped z -ROCs (e.g., Slotnick & Dodson, 2005). This approach seems misguided to us for two reasons. First, there is nothing particularly weird about a relational recognition memory test. All recognition memory tests are really tests of source memory. That is, in tests of item recognition, participants are not asked to indicate if they have ever seen the test items before but are asked if they remember having seen the item in the particular experimental context. Source recognition tests simply make the recollective demands of the task more salient. Second, given that the DPSD model provides a way of accounting for both item recognition and relational recognition using the same basic mechanisms, it should be preferred over an approach that would propose different mechanisms for the two domains.

Wixted (2007) conceded that the UVSD model cannot account for relational recognition ROC data and discussed several modifications that might be considered, including the dual-process interpretation of the UVSD model, the some-or-none (SON) model, and the mixture model. Some of these suggestions seem worthwhile, whereas others appear to be inadequate. The model that Wixted mentioned most frequently is the one that he argued has virtually unanimous support—the dual-process interpretation of the UVSD model. However, as we just showed, this version of the model still produces Gaussian strength distributions and thus cannot account for U-shaped z -ROCs found in tests of relational recognition. So, despite the important advance of incorporating recollection and familiarity into the model, this version still fails to account for the ROC results that were most problematic for that model.

However, there are a number of possible ways to modify the UVSD model so that it can account for these data, most of which involve moving beyond pure signal-detection models toward hybrid models—that is, models that incorporate both threshold and signal-detection assumptions. The first alternative, and obviously our choice, is to move toward the DPSD model and treat recollection as a threshold process. Such a threshold assumption could be implemented in many ways though. It is not necessary to remain agnostic about the shape of the recollection distribution, as the DPSD model does, in order to accommodate a threshold process. For instance, the variable-recollection dual-process (VRDP) model (Sherman et al., 2003) is an extension of the DPSD model that makes the same assumptions but assumes in addition that the above-threshold recollected items form a Gaussian distribution. Because the threshold assumption is maintained, the model can produce U-shaped relational ROCs. In fact, if recollection leads to

high memory strength relative to familiarity, this model collapses into the DPSD model. A consideration of this model is important because it indicates that the threshold assumption about recollection is not inconsistent with the notion that recollection strength might be Gaussian, and it highlights the importance of the threshold notion that recollection can fail. Another extension of the DPSD model, and another way of incorporating a threshold recollection process, is the SON model of Kelley and Wixted (2001). It was developed to account specifically for associative recognition and includes a UVSD process for associative information, an equal-variance signal-detection process for item information, and a threshold recollection process. This model differs from the VRDP model in that it includes a summing assumption similar to that of Wixted's (2007) current model. Because the SON model includes a threshold process, it can account for U-shaped z -ROCs seen in associative recognition.

We believe that both the VRDP and SON extensions of the DPSD model hold a great deal of promise in furthering understanding of recollection and familiarity, but they have yet to be adequately tested, and it is not yet clear whether their new assumptions are justified. That is, little work has been conducted with these models, and thus it is unknown whether the additional parameters are needed or whether they behave in reasonable ways. Another potential limitation is that the large number of parameters (i.e., a minimum of five for SON and a minimum of four for VRDP) may restrict their utility. In addition, although the above-threshold recollection strength distribution might be Gaussian in shape, studies designed to directly assess this assumption will need to be conducted.

Another related approach that also has considerable promise is the mixture model (DeCarlo, 2002, 2003). Like the DPSD model, it includes an equal-variance signal-detection process and a probabilistic (i.e., threshold) parameter representing an attentional encoding process. The underlying logic of the model is intuitively appealing—it assumes that some items are encoded and other items are not encoded at all. This, of course, makes good sense; participants may miss some studied items because of a failure of attention. Thus, items that are attended increase in memory strength, those that are unattended do not increase, and recognition decisions are based solely on the resulting memory strength. We see this as a promising model because it attempts to quantify processes at encoding, which few other ROC models have done. However, the focus on encoding may also prove a liability to the model given evidence demonstrating that retrieval conditions can also be important determinants of recognition performance. According to the DPSD model, recollection may fail because of inadequate encoding, but other factors such as delay period or the specific retrieval conditions should also be expected to influence the probabilistic process influencing recognition. In addition, although the model assumes two processes at encoding (attention and memory strengthening), it assumes a single process at time of retrieval (familiarity assessment); thus, it is not clear how it would deal with the dissociations between recollection and familiarity. Although the utility of the mixture model is largely unknown because it has not yet been very widely applied, we believe that future studies exploring this approach will be informative.

Finally, one could modify the dual-process UVSD model by doing away with the Gaussian assumption of signal-detection theory altogether and using different probability distributions—

ones that are capable of producing both linear and curvilinear z -ROCs. In fact, Wixted (2007) suggested in a footnote that one might adopt non-Gaussian strength assumptions with an additional asymmetry parameter. However, this approach has not yet been explored, and if the signal-detection model's assumptions are relaxed to this extent, it is not clear whether the model would make any predictions about recognition memory ROCs.

Moving Beyond ROCs

Although the initial motivation for the DPSD model was to account for ROC data, the main approach to testing the model has been to assess its utility across a wide variety of test procedures and to test for convergence across various measurement methods (e.g., Yonelinas, 2001b). The rationale behind this approach is the belief that no one procedure provides a process-pure index of recollection or familiarity and that only through convergent operations can we hope to come to a full understanding of the processes underlying memory. Wixted (2007) used the term *process pure* in a different manner, but his interpretation of the model's predictions indicates that he has failed to appreciate this important assumption of our work. This leads to confusion regarding the interpretation of RK, relational, and amnesia results. We clarify our position on these methods and the model's predictions below, but in brief, our position is that process purity does not exist at any level of measurement. Researchers may be able to provide more and more rarefied estimates of psychological processes as methods become more sophisticated, but true process purity is probably an unattainable ideal.

RK Reports Can Be Used to Assess Recollection and Familiarity, But They Do Not Provide Process-Pure Measures of These Processes

In the RK procedure (Tulving, 1985), participants are told to respond "remember" if they can recollect qualitative details about the study event and to respond "know" if the item is familiar but not recollected. Given these instructions, it might seem reasonable to treat the proportion of remember and know responses as pure measures of recollection and familiarity, respectively. Although we believe that the existing evidence indicates that people do have access to information yielded by recollection and familiarity and that they generally can report on these experiences under the appropriate test conditions, we have argued against a process-pure interpretation of RK reports for several reasons.

First, because remember and know responses are mutually exclusive, the raw proportion of know responses underestimates the likelihood that items are familiar and thus cannot be used as a measure of familiarity (Yonelinas & Jacoby, 1995). Second, this account does not correct for response bias effects, and thus it ignores the interpretive problems that can arise when participants falsely recognize new items. We have adopted methods that take into account the overlap between recollection and familiarity and that incorporate response bias and false recollection using signal-detection and threshold methods for familiarity and recollection, respectively (e.g., Yonelinas, 2001b; Yonelinas & Jacoby, 1995).

Third, the process-pure account assumes that participants have perfect access to the products of recollection and familiarity and that they always respond perfectly in accord with the RK instruc-

tions. The RK procedure, however, is a subjective report method, and without convergent evidence from other more objective measurement methods, it is always open to the classic criticisms of introspectionism (Yonelinas, 2001a). Although RK reports can be quite useful, it is now clear that the manner in which participants use RK responses can be influenced by factors such as how the test is administered (e.g., Bodner & Lindsay, 2003). For example, several studies have collected recognition confidence judgments and RK reports within the same test in order to determine whether recollection and familiarity estimates derived from RK responses matched those derived from an ROC analysis. In some of these studies, the majority of remember responses (e.g., 95%) were associated with the highest level of recognition confidence (Yonelinas, 2001b; Yonelinas et al., 1996), and the two methods produced comparable process estimates. The convergence of the estimates derived from the RK and the ROC measures attest to the validity of the RK reports (also see Yonelinas, 2001b, 2002; Yonelinas et al., 2002, for validation of these methods using other methods such as response deadline procedures, the process dissociation procedure, and structural equation modeling).

It is important to note, though, in other RK studies, remember responses have been associated with a wider range of confidence (Rotello, Macmillan, & Reeder, 2004; Stretch & Wixted, 1998), and the RK estimates did not converge as closely with those of the ROC analysis. However, there appears to be a very good reason for this. In the studies in which remember responses elicited primarily the highest confidence ratings and the estimates from the two methods converged, participants were instructed to respond “remember” only if they could report what they recollected about the item if asked. This was done to ensure that they did not respond “remember” on the basis of high levels of familiarity. In contrast, in studies in which remember responses were associated with lower levels of recognition confidence and estimates from the two methods diverged, this instruction was not included. In fact, Rotello, Macmillan, Reeder, and Wong (2005) directly compared these test instructions and replicated the differences just described within a single experiment. In addition, the false remember rates were unusually high in the cases where the reportability instruction was not included in the definition of recollection (e.g., 16% in the Rotello et al., 2005, neutral condition, compared with a rate of between 1% and 3% in the Yonelinas, 2001b, study). With a few notable exceptions (e.g., false memory paradigms, studies of older adults, and studies of amnesic patients), false remember rates rarely reach these high levels (e.g., in Dunn’s, 2004, review of 400 RK conditions, the average was only 5%).

The results suggest that the participants can sometimes use remember responses even when they do not recollect anything, and in these cases, remember reports do not provide very good measures of recollection (i.e., they do not converge with other measures of recollection). The standard instructions define recollection as remembering a specific detail about an item’s prior presentation, and it seems that participants should be capable of reporting what it is they remember. Indeed, participants have been shown to report those details fairly articulately when asked to do so with the standard instructions (e.g., Gardiner, Ramponi, & Richardson-Klavehn, 1998). Although asking that participants be able to justify their RK responses may not always be necessary, we suspect that it is prudent to do so to ensure that participants respond in accord with the RK distinction. In any case, when under

standard conditions healthy participants falsely remember a large portion of the nonstudied items, one must entertain the possibility that they are not responding in agreement with the RK instructions.

Wixted (2007) took a more pessimistic view of the RK method and argued that it cannot be used to gain insight into the processes of recollection and familiarity at all because participants either cannot or will not comply with RK instructions. That is, participants do not make remember responses on the basis of recollection alone, but instead sum recollection and familiarity signals together, and make a remember response only if the summed information exceeds the remember criterion. Conversely, know responses are not based on familiarity in the absence of recollection because recollection is never absent. Because recollection is assumed to reflect a Gaussian signal-detection process, every item will have some degree or amount of recollection that will be added to familiarity.

However, we find little compelling evidence to support the claim that people do not differentially weight experiences of recollection and familiarity when making remember and know responses. Given the compelling subjective experiences of recollection and familiarity that we have all had, it is hard to believe that people are unable to report when they retrieve qualitative information and when they recognize something as old but cannot recall anything about it. By Wixted’s (2007) view, an item with high recollection strength and low familiarity strength might lead to a remember response, but a comparable item with high familiarity strength and low recollection strength could support exactly the same remember response. In contrast, we think that people do have access to, and can report, recollected information and familiarity in the absence of recollection, even though both their access and reporting may be imperfect. In our view, the convergence observed between RK and various other measurement methods argues strongly that participants can report on the occurrence of recollection and familiarity. In addition, as discussed earlier, U-shaped z -ROCs indicate that recognition does not simply reflect the summing of recollection and familiarity Gaussian strength values as Wixted’s model assumes.

Relational Recognition Tests, Like Tests of Source Memory and Associative Recognition, Do Not Provide Process-Pure Measures of Recollection

Because relational recognition tests call for participants to remember qualitative information about a study event, some have assumed that they provide process-pure tests of recollection (e.g., Qin, Raye, Johnson, & Mitchell, 2001; Slotnick & Dodson, 2005; Slotnick et al., 2000; Wixted, 2007). As such, it has been argued that only the threshold component of the DPSD model should be necessary to account for performance and, therefore, that relational recognition ROCs should always be linear (e.g., Slotnick & Dodson, 2005; Wixted, 2007). It’s clear that relational recognition tests usually rely more heavily on recollection than do item recognition tests (e.g., Hockley & Consoli, 1999). However, it is also clear that both recollection and familiarity can contribute to performance on these tests. For example, persons with amnesia often perform more poorly on associative than item recognition memory tests but can, under some conditions, exhibit comparable levels of performance on the two types of tests (Vargha-Khadem, Gadian, & Mishkin, 2001), suggesting that familiarity can contribute to relational rec-

ognition tests. On the basis of such findings, as well as our early ROC studies, we have argued that single-process models, such as ones that include only recollection, are inadequate and that a model that includes both recollection and familiarity is necessary to account for performance on relational recognition tests (e.g., Quamme, Yonelinas, & Norman, 2005; Yonelinas, 1997, 1999b, 2001b; Yonelinas et al., 1999). This means that although relational recognition ROCs should generally be flatter than those seen in item recognition, they should still show some of the curvilinearity that is due to familiarity. It is only when the contribution of familiarity can be completely eliminated that the ROCs should become linear. We have been quite clear that we do not expect relational recognition tests to be process-pure measures of recollection (e.g., Yonelinas, 1997, 1999b; Yonelinas et al., 1999). In fact, we have demonstrated that familiarity can provide a significant contribution to performance on these tests (e.g., Yonelinas, 1999a; Yonelinas et al., 1999).

Nonetheless, Wixted (2007) took the findings of curvilinear ROCs in relational tests as evidence that the DPSD model fails. However, this is exactly what the model predicts if one assumes that recollection and familiarity contribute to performance. Curvilinear ROCs in relational recognition are only inconsistent with the DPSD model if one makes the incorrect assumption that these tests provide a process-pure measure of recollection. We have never made that assumption, and therefore, this criticism is misplaced. We agree that the relational recognition ROC results argue strongly against single-process threshold models (Slotnick et al., 2000; Wixted, 2007; Yonelinas, 1999a), but one should not confuse those threshold models with the DPSD model.

Another way this process-pure assumption about relational recognition has led to inappropriate conclusions is reflected in the work of Slotnick and Dodson (2005). According to Wixted (2007), "Slotnick and Dodson (2005) recently offered what would appear to be the decisive test of the ability of the UVSD and DPSD models to accommodate source memory ROCs" (p. 161). Slotnick and Dodson collected both old–new confidence and source confidence ratings for each item and then plotted source ROCs as well as source ROCs that were conditionalized on recognition confidence. The traditional source ROCs exhibited a U shape in z space, as is typically seen in relational tests. They then plotted what they referred to as a *refined* source ROC by including only the items that had received a high-confidence old judgment (i.e., a 5 or a 6 on a 6-point scale). This conditional source z -ROC was found to be less U shaped (i.e., flatter) than the original source z -ROC, and they argued that such a finding is problematic for the DPSD model.

However, neither Slotnick and Dodson (2005) nor Wixted (2007) attempted to fit the DPSD model to the ROC data, and a more careful consideration indicates that the observed pattern of results, rather than being a definitive falsification of the model, follows rather naturally from the model. Although there may be various ways of accounting for the data with the model, one simple way is to assume that the removal of the low-confidence responses effectively eliminates items for which there was the least amount of familiarity-based memory information. That is, if a participant thinks that a test word was not studied at all, one would expect that familiarity should be of little use in supporting an accurate source judgment about that item. Thus, the items remaining in the refined source ROC will be more effective at supporting source discriminations, which would lead to an apparent increase in the extent to

which familiarity contributed to the source ROC. Because familiarity leads to linear z -ROCs, the refined z -ROC should become more linear, in agreement with what was observed.⁵

Thus, finding that relational ROCs can exhibit some degree of curvilinearity is not an indication that recollection is a signal-detection process or that the DPSD model cannot account for relational ROCs. This is in sharp contrast to Wixted (2007), who treated findings of curvilinear source and associative ROCs as somehow damning of the DPSD model. Further, he treated the pattern of refined source ROCs as definitive evidence that the DPSD model fails. However, those ROC results follow naturally from the assumptions of the DPSD model, which assumes that although recollection will be more useful, both processes will contribute to relational recognition performance.

Neural Studies of Recognition Have Generally Supported the Predictions of the DPSD Model

Although signal-detection models such as the DPSD and UVSD models are sometimes treated as purely functional models of behavior, there is a growing trend to use these types of models to understand results from neuroscientific studies such as event-related potential (ERP), functional magnetic resonance imaging (fMRI), and amnesia studies. Wixted (2007) reviewed some of these studies and suggested that the DPSD model is not particularly useful for understanding these results. However, a broader reading of that literature indicates that the data provide strong support for a number of predictions of the DPSD model. In contrast, although the UVSD model can provide a post hoc account of some of these effects, it has not yet proven particularly useful in furthering the understanding of these results.

The DPSD model has been used to generate several general predictions about the neural substrates of recognition memory.

⁵ To verify that the DPSD model could account for the observed flattening of the source z -ROC, we started by fitting the model to the original source ROC, which resulted in probability estimates of recollection (.24 and .22 for the male and female voices, respectively) and a d' estimate for familiarity (.47). These calculations were based on the average data from Experiments 1 and 2, but the same pattern of results was obtained when each experiment was examined separately. To determine the effects of removing low-confidence recognition responses, we then generated an ROC using the same recollection parameters, but we multiplied the familiarity parameter by two. We kept the recollection estimates unchanged because we assumed that recollection should lead to relatively high-confidence recognition responses and thus should not be greatly affected by removing the low-confidence items. We doubled the familiarity parameter on the basis of the assumption that the items that were removed from the analysis on the basis of low recognition confidence (about half of the total number of items) would not be expected to support accurate source discriminations; thus for the remaining items, familiarity would be approximately twice as effective. These parameters were used along with the DPSD equations to generate a predicted ROC, which was plotted across the same range of false alarms as observed in the conditionalized ROC. This function was then assessed for nonlinearity in the same way as the observed ROC data. In contrast to the initial source ROC, which had a quadratic value of .26, the predicted conditional source ROC had a quadratic value of .16, which was comparable to the quadratic value derived from the observed data (.13). Thus, as in the observed data, our calculations indicate that the DPSD model can produce conditionalized z -ROCs that are flatter than the original z -ROCs.

First, if recognition reflects the operation of two separate processes, then neuromonitoring studies should reveal evidence for at least two dissociable neural signals, one for each of these processes. A more interesting point is that one of these neural correlates should be modulated in a continuous manner across recognition confidence (i.e., familiarity), whereas the other should be preferentially related to high-confidence old judgments (i.e., recollection). In addition, these two signals should be preferentially related to other measures of familiarity and recollection, respectively, such as those obtained in RK studies. Moreover, because we have assumed that the hippocampus is required for recollection, but not familiarity, neuroimaging studies should reveal a link between recollection and the hippocampus, whereas other regions should be involved in familiarity. In fact, if recent animal models of recognition are correct (e.g., Aggleton & Brown, 1999), then the perirhinal cortex (i.e., a region in the anterior medial temporal lobe surrounding the hippocampus) should be critical for familiarity. Finally, although patients with extensive medial temporal lobe damage should have deficits in recollection and smaller deficits in familiarity, patients with selective hippocampal damage should exhibit selective recollection deficits. As it turns out, the data provide reasonably strong support for all of these predictions.

For example, ERP studies have identified two dissociable ERP correlates of recognition, a frontocentral negativity that onsets about 400 ms after stimulus onset and a late positive component largest over the right parietal region that arises approximately 500 ms after stimulus onset (for reviews, see Curran, Tepe, & Piatt, *in press*; Friedman & Johnson, 2000; Mecklinger, 2000; Rugg & Yonelinas, 2003; see also Yovel & Paller, 2004). The slower component has been linked to recollection in the sense that it is associated with remember compared with know responses, accurate compared with inaccurate source recognition responses, and accurate compared with inaccurate judgments in plurality-reversed recognition. In contrast, the earlier effect has been linked with familiarity in the sense that it is associated with accurate recognition but does not distinguish between remembering and knowing, accurate compared with inaccurate source recognition, or accurate compared with inaccurate plurality recognition judgments. Note that, consistent with the DPSD model, these ERP correlates of recollection and familiarity have been shown to be sensitive to different ranges of response confidence, with the familiarity correlate increasing monotonically as a function of confidence and the recollection component found only for high-confidence old responses (Curran, 2004; Woodruff, Hayama, & Rugg, *in press*). Other studies manipulating response criteria have found evidence consistent with the link between the familiarity component and recognition confidence as well (e.g., Azimian-Faridani & Wilding, 2006; Windmann, Urbach, & Kutas, 2002).

Studies using fMRI have provided additional support for the DPSD model. Although Wixted (2007) cited a few neuroimaging studies in his review, he failed to point this out. For example, fMRI studies using RK, relational recognition, and ROC confidence methods have indicated that recollection is consistently associated with hippocampal activation (e.g., Cansino, Maquet, Dolan, & Rugg, 2002; Daselaar, Fleck, Dobbins, Madden, & Cabeza, *in press*; Davachi, Mitchel, & Wagner, 2003; Eldridge, Engel, Zeineh, Bookheimer, & Knowlton,

2005; Eldridge, Knowlton, Furmanski, Bookheimer, & Engel, 2000; Fenker, Schott, Richardson-Klavehn, Heinze, & Duzel, 2005; Giovanello, Schnyer, & Verfaellie, 2004; Jackson & Schacter, 2004; Kensinger & Schacter, 2006; Kirwan & Stark, 2004; Montaldi, Spencer, Roberts, & Mayes, 2006; Ranganath et al., 2003; Uncapher & Rugg, 2005; Weis et al., 2004; Wheeler & Buckner, 2004; Woodruff, Johnson, Uncapher, & Rugg, 2005; Yonelinas, Otten, Shaw, & Rugg, 2005) and only rarely with perirhinal activation (Eldridge et al., 2005; Fenker et al., 2005; Gold et al., 2006; Jackson & Schacter, 2004; Kirwan & Stark, 2004). In contrast, familiarity is consistently associated with perirhinal activation (Daselaar et al., *in press*; Davachi et al., 2003; Gold et al., 2006; Gonsalves, Kahn, Curran, Norman, & Wagner, 2005; Henson, Rugg, Shallice, Josephs, & Dolan, 1999; Kensinger & Schacter, 2006; Kirwan & Stark, 2004; Montaldi et al., 2006; Ranganath et al., 2003; Uncapher, Otten, & Rugg, 2006; Uncapher & Rugg, 2005; Weis et al., 2004) and only rarely related to changes in hippocampal activation (e.g., Daselaar et al., *in press*; Eldridge et al., 2005; Gold et al., 2006; Yonelinas et al., 2005). Moreover, virtually every study that has correlated continuous changes in recognition confidence with activation has failed to find monotonic relationships between hippocampal activation and memory strength, whereas such correlations have been consistently observed in the perirhinal cortex (Daselaar et al., *in press*; Gonsalves et al., 2005; Montaldi et al., 2006; Ranganath et al., 2003). This is exactly what would be expected if recollection supported high-confidence recognition responses and familiarity varied across the entire range of recognition confidence.

As evidence against the claim that recollection is selectively dependent on the hippocampus, Wixted (2007) cited a study by Rutishauser, Mamelak, and Schuman (2006) showing that human hippocampal neurons differentiate between old and new items but not between correct and incorrect source judgments. This is taken as evidence that the hippocampus must be supporting familiarity-based recognition rather than recollection. Although these authors did find that successful source recollection was not required for neurons to exhibit a familiarity response, they also found that successful item recognition was not required for these neurons to exhibit a familiarity response either. Thus, although Rutishauser et al.'s findings are certainly interesting, it is not immediately clear how these findings relate to either recognition or source recognition performance.

Studies of medial temporal lobe amnesia have provided more support for the DPSD model. This too was overlooked by Wixted (2007). Studies using RK, relational, and ROC methods have indicated that patients with damage including the hippocampus and the surrounding medial temporal cortex have deficits in recollection as well as smaller, but consistent, deficits in familiarity (e.g., Blaxton & Theodore, 1997; Cipelotti et al., 2006; Kishiyama, Yonelinas, & Lazzara, 2004; Knowlton & Squire, 1995; Moscovitch & McAndrews, 2002; Schacter, Verfaellie, & Anes, 1997; Schacter, Verfaellie, & Pradere, 1996; Verfaellie, Cook, & Keane, 2003; Verfaellie & Treadwell, 1993; Yonelinas, Kroll, Dobbins, Lazzara, & Knight, 1998; Yonelinas et al., 2002). In contrast, various patients with damage expected to be restricted to the hippocampus exhibit selective recollection deficits as measured using ROC, RK, and structural equation modeling methods (Aggleton et al., 2005;

Yonelinas et al., 2002). Although one group of such patients (Manns, Hopkins, Reed, Kitchener, & Squire, 2003) appears to have deficits in both recollection and familiarity, it has been pointed out that without histological data we cannot rule out the possibility that these familiarity deficits were due to damage outside the hippocampus (Yonelinas et al., 2004). In fact, an ROC study in rats, in which the lesions were restricted to the hippocampus, replicated the former human results and showed that selective hippocampal damage leads to selective recollection deficits (Fortin, Wright, & Eichenbaum, 2004). Wixted (2007) expressed concerns about this study, but the convergence of results from nonhuman species with human patient studies and human neuroimaging results provides compelling evidence in favor of the claim that the hippocampus is selectively important for recollection.

Another consistent finding in the amnesia literature, which the DPSD model predicts, is that the item ROCs of patients with amnesia are often very close to symmetrical (Cipolotti et al., 2006; Wais, Wixted, Hopkins, & Squire, 2006; Yonelinas et al., 1998, 2002), as might be expected if they rely primarily on a process that is well described as an equal-variance signal-detection process (i.e., familiarity). Although this is an important finding and is in stark contrast to the asymmetrical ROCs typically observed in control participants, it is important to realize that perfectly symmetrical ROCs are expected only if recollection is completely eliminated. The fact that the resulting ROCs were symmetrical in most studies of people with amnesia suggests that recollection was greatly impaired in these cases by medial temporal lobe damage. However, ROCs of patients with amnesia should not be expected to be perfectly symmetrical in all conditions, and in fact, they are not. One amnesic patient, for instance, was found to have normal familiarity and a moderate recollection impairment (Aggleton et al., 2005). Thus, his ROCs were more symmetrical than those of control participants, who performed at comparable overall levels of recognition, but his ROCs were still slightly asymmetrical. Similarly, Wais et al. (2006) found symmetric ROCs for a group of amnesic patients and the typical asymmetric ROCs in a control group. However, when they tested the amnesic participants with 10-item lists, they found that the ROC was now slightly asymmetric. Although they did not collect enough responses to examine individual ROCs, the result suggests that amnesic participants' ROCs may be asymmetric when they are tested using very short lists. Wixted (2007) interpreted this result as challenging for the DPSD model. However, such results pose a problem to the model only if it is assumed that amnesic patients must always provide a process-pure measure of familiarity and that their ROCs should therefore be perfectly symmetrical. In fact, we have never made that assumption (see Yonelinas et al., 1998). Although amnesic participants should typically have a greater deficit in recollection than familiarity, one cannot expect their recognition performance to provide a process-pure measure of familiarity. More mildly impaired patients should have some preserved recollective ability, and under short-list conditions, one would also expect amnesics to recollect some small proportion of the studied items.

How does the UVSD model fare with respect to the neural data? The neural results parallel the behavioral results in showing that recognition memory relies on recollection and famil-

ilarity, rather than on a single memory process. Thus, a single-process interpretation of the UVSD model immediately runs into difficulties. However, if one allows for the possibility of separate recollection and familiarity processes, as Wixted (2007) did, then the model can provide post hoc accounts for at least some of the neural results. However, a number of these results remain poorly explained by this approach. The finding that there are two distinct sets of electrophysiological and hemodynamic signals corresponding to recollection and familiarity can of course be accounted for by such a dual-process model. In addition, as in the DPSD model, the neural signals that were found to increase monotonically with recognition confidence are consistent with the notion that familiarity reflects a signal-detection process. However, why the recollection correlates do not also increase in a similar manner is less clear. There is nothing in the model that would lead one to predict that recollection should be related selectively to the high-confidence old responses. There may of course be additional post hoc assumptions that could be made to accommodate these results. For example, Wixted (2007) suggested that memory strength could be computed by different brain regions that are sensitive to different levels of memory strength. Thus, the hippocampus might respond only to the highest confidence recognition responses, whereas the perirhinal cortex responds to lower levels of memory strength. But in order to account for confidence, RK, and relational data, one must assume that the strength that the hippocampus supports carries with it the subjective experience of remembering and the ability to make accurate relational recognition judgments, whereas the strength supported by the perirhinal cortex is associated with feelings of familiarity in the absence of recollection and does not support accurate relational recognition judgments. This, of course, comes very close to agreeing with the assumptions of the DPSD model. Wixted also suggested another possibility—that although recollection itself is a signal-detection process, autoeonic consciousness (the awareness of remembering) is a threshold process that is uniquely related to the hippocampus. We agree that it is useful to use a threshold process to deal with RK results but do not see the necessity of assuming that the threshold nature of recollection disappears in confidence or relational recognition tests, particularly because hippocampal activation is found in all three of these cases, not just remember reports. Although these options are unlikely to exhaust the possible modifications that would allow the model to account for the neural data, in its current form it does not provide a particularly compelling account of the ERP or fMRI data. In any case, the modifications that would seem necessary to bring the UVSD model in line with the existing data are exactly those that would make it more similar to the DPSD model.

How does the UVSD model account for the amnesia results? The dual-process version of the model could in principle account for the overall pattern of results seen in amnesic participants by assuming that recollection relies on the hippocampus, whereas familiarity relies on other regions such as the perirhinal cortex. In addition, the model can produce the asymmetrical ROCs as seen in control participants as well as the symmetrical ROCs often reported in the amnesic participants because it has a free parameter for the variance ratio. So the ROCs can be fit quite well by the UVSD model. How one interprets the param-

eter estimates derived from the UVSD model, however, is not yet entirely clear. According to the UVSD model, the amnesic patients appear to suffer from a severe impairment in the old–new variance component and a less severe impairment in the memory strength component. More specifically, the model suggests that patients with medial temporal lobe damage experience an increase in the strength of items as a result of study but, unlike control participants, little or no increase in the variance of the old items. Why the medial temporal lobe would be more important for the variance component than the memory strength component in recognition is not yet clear. Moreover, why the extrahippocampal regions would increase only strength while leaving the variance component unaffected is also unclear. Currently there is nothing in the model linking the variance component to any particular brain region(s) or to levels of recollection or familiarity. In any case, the UVSD model supports conclusions similar to those based on the DPSD model in the sense that medial temporal lobe amnesia cannot be interpreted as a simple deficit in memory strength. In fact, if anything, memory strength seems to be relatively preserved in many cases, and the largest effect is on the variance component.

Limitations of the DPSD Model

The relational recognition data and neural data together provide strong support for hybrid models over pure signal-detection models and specifically for the DPSD over the UVSD model. Of the hybrid models proposed (DPSD, VRDP, SON, and mixture), we find DPSD to provide the best account of the recognition data so far, but we are also aware of its limitations. It is clearly too simple in that it involves only two processes. Given the complexity of a recognition decision, two processes are unlikely to account for the full range of performance (e.g., consider the attention and metacognitive processes involved). Also, the model cannot in its current form account for all the ROC data. For instance, the DPSD model cannot predict negative quadratic terms without modification. Figure 2 includes cases that appeared to produce negative quadratics, and Heathcote (2003) reported negative quadratics in several item recognition tests. Future work is necessary to determine whether there are conditions in which inverted U-shaped z -ROCs are reliably observed or whether they are due to noise (e.g., Malmberg & Xu, 2006; Ratcliff, McKoon, & Tindall, 1994) or even simple experiment-level error variance. There are also other results that are clearly problematic for the model. For example, Sherman et al. (2003) found that item z -ROCs were U shaped for control participants but were S shaped for participants who encoded items under the amnesic effects of scopolamine. They showed that a modified DPSD model, in which a threshold recollection process that produced a Gaussian recollection distribution with low variance, provided a better fit than the original DPSD model. Moreover, Macho (2004) examined a previous study of associative recognition and showed that increasing study repetitions led to a decrease in recollection, an effect that makes little sense. Thus, the behavioral ROC data already present some important challenges to the DPSD model.⁶ However, almost all of these cases also prove to be a challenge for the UVSD model, and they appear to be relatively minor compared with the failure of the core Gaussian assumption of the UVSD model.

In addition, although the DPSD model predictions for the neural data have been consistently supported, the neuroimaging

results still cannot be adequately explained by the model because it currently tells very little about the role of regions outside the hippocampus. For instance, regions in the parahippocampal and parietal cortex are often found to be related to recollection (e.g., Ranganath et al., 2003), but ideas on their roles in recollection have not yet been adequately developed (although see Eichenbaum, Yonelinas, & Ranganath, 2006). And of course there are regions that are not directly related to recollection or familiarity but that are still critical for recognition performance, such as areas that track confidence independent of whether an item is judged old or new (Henson, Rugg, Shallice, & Dolan, 2000). We believe that developing a more sophisticated understanding of the various brain regions involved in recognition reflects an important challenge for all future models of recognition.

Conclusion

The DPSD model has played a critical role in guiding recognition memory research. For example, it led to the discovery that z -ROCs in relational recognition tests are U shaped (e.g., Yonelinas, 1997), a finding that is incompatible with the Gaussian assumption underlying the UVSD model. It has also proven useful in guiding recent electrophysiological, imaging, patient, and animal lesion studies (e.g., Fortin et al., 2004; Ranganath et al., 2003; Woodruff et al., in press; Yonelinas et al., 2002). In all of these areas, the model has been met with considerable success. Nonetheless, it is in no way complete, and various challenges remain. Moreover, several alternative models have recently been proposed, many of which build on the assumptions of the DPSD model. Future work is important to determine which of these models provides the best account for recognition, but it now seems clear that pure signal-detection models such as UVSD are not viable models of memory. Although Wixted's (2007) incorporation of separate recollection and familiarity processes into the traditional UVSD model is an important step forward, in itself it is not adequate to account for existing ROC data.

⁶ Wixted (2007) also noted a recent study that found that the DPSD model's yes–no parameters did not predict forced-choice performance very well (Smith & Duncan, 2004). However, participants in that study were instructed to use each confidence key an equal number of times—that is, they were essentially instructed not to respond in accord with the DPSD model (which predicts an uneven distribution of confidence ratings due to the contribution of recollection). If participants do use each response key equally often then the number of 6 responses will be equal to the total number of test items divided by the number of confidence bins (e.g., 140 old plus 140 new in that experiment, divided by 6, which is 47). What this means is that participants could only place a maximum of about 33% of the old items (47/140) in the high-confidence bin. If a participant recollected more than 33% of the old items, which is likely given the high level of observed performance, then they would have been forced to distribute the recollected items across lower confidence bins. This will lead the DPSD model to mis-fit the data and will artifactually make it look like the UVSD model is fitting better than it really does. Examining forced-choice and confidence ratings may provide another interesting way of testing the models but it is clear that further work is necessary before concluding that the DPSD model cannot predict forced-choice performance.

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Postscript

Colleen M. Parks and Andrew P. Yonelinas
University of California, Davis

In our comment on Wixted (2007a), we argued that most of the concerns he initially raised reflect misconceptions about the dual-process signal-detection (DPSD) model's underlying assumptions (e.g., threshold recollection can, in fact, be graded, and no task or population is expected to provide process-pure measures). Wixted's (2007b) response does not directly challenge these arguments, but he

did include three new arguments about previous studies—none of which stand up to careful examination. First, he argued that the majority of the z -transformed receiver-operating characteristics (z -ROCs) in Heathcote (2003) were not curved downward (a result that is problematic for both models), and to support this argument, he selected results from four conditions in a single experiment (i.e., Experiment 3). But an examination of Experiments 1, 2, and 3 shows that 15 out of 19 conditions did have z -ROCs with an inverted U shape, thus supporting our original claim. Further, Wixted suggested that even if such a pattern was observed, the unequal-variance signal-detection (UVSD) model could account for it if it were allowed a

guessing process. Of course, a point he overlooked is that a guessing process would allow both models to account for this shape (Yonelinas, 1999b)—highlighting that item recognition has not been particularly “probative” with respect to these two models. Second, Wixted noted that the UVSD model showed “impressive predictive validity” (Wixted, 2007b, p. 204) in Smith and Duncan’s (2004) study that examined yes–no and forced-choice recognition and argued that the instruction we disputed (i.e., to spread responses equally among confidence ratings) is irrelevant because some participants ignored it. However, it should not be surprising that when instructed to respond contrary to the DPSD model and in accord with the UVSD model, the data are better predicted by the latter model (even if not all participants complied perfectly with the instructions). A third set of data that Wixted argued supports the UVSD model is Slotnick and Dodson’s (2005), in which conditional source ROCs were found to be more curvilinear than traditional ROCs. Wixted now conceded that the DPSD model provides a very good fit for that data, but he instead focused on the behavior of specific parameter estimates in one of the three experiments in that article. Wixted argued that a .10 decrease in DPSD recollection estimates from the original to conditionalized ROCs presents a real problem for the model. However, this pattern was observed only in the one experiment he chose to describe. In contrast, in Slotnick and Dodson’s Experiment 1, the recollection estimates increased, rather than decreased, by about .10, whereas in Experiment 2 the recollection estimates increased for one source but decreased for the other. Thus, the results of this conditional ROC analysis do not seem to tell any clear story.

There are two more substantive points on which we still disagree. First, Wixted (2007b) argued that the neural data are irrelevant to the current debate because they presuppose the validity of the DPSD model. It is true that many studies have been designed explicitly to test the predictions of the DPSD model, but that does not render the resulting data biased or irrelevant. In fact, a number of neural studies have specifically examined the results in light of both the DPSD and UVSD models (e.g., Fortin, Wright, & Eichenbaum, 2004; Gonsalves, Kahn, Curran, Norman, & Wagner, 2005; Montaldi, Spencer, Roberts, & Mayes, 2006; Woodruff, Hayama, & Rugg, in press; Yonelinas, Otten, Shaw, & Rugg, 2005), and in general, these studies have concluded in favor of the DPSD model. We suspect that the reason the DPSD model has been adopted so widely is not only that it provides a better account of the data but also that it offers psychologically meaningful and neurologically plausible constructs. In contrast, there has been no successful attempt to ground the variance ratio component underlying the UVSD model to any neuroscientifically meaningful construct, which has rendered it of less use in guiding current research.

Another major point of disagreement in our approaches is whether tasks or responses are assumed to provide process-pure measures of psychological constructs. We concentrate here on relational recognition tasks as an example, but the same general arguments apply to remember–know tasks and amnesia studies. Wixted theorized that familiarity should not be useful in source recognition tests and even went so far as to refer to source recognition as a *recollection test*. He then quoted Yonelinas (1997, 1999a) out of context in ways that make it appear as though we agree that these tests provide process-pure measures of recollection, despite the fact that we argued emphatically against such a position in our reply. The data, we believe, are abundantly clear on

this issue: Recognition tasks—even source recognition tasks—are not process pure (Jacoby, 1991; Yonelinas, 1999a; Yonelinas, Kroll, Dobbins, & Soltani, 1999).

Despite these disagreements, we do agree with Wixted’s (2007b) contention that the relationship between recollection and confidence is at the very heart of the issue when contrasting our approaches to recollection and familiarity. In fact, it is exactly that relationship that our Figure 2 (the distribution of quadratic coefficients) speaks to. Although the item recognition data fail to discriminate between the two models, the relational recognition data are very clear. That is, when examining the confidence-based ROCs in these tests, the resulting z -ROCs are U shaped, demonstrating quite conclusively that recollection does not reflect the simple signal-detection process that Wixted has assumed but rather is more consistent with threshold models that assert that recollection can, and does, sometimes fail.

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