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Research Article

Recollection Is a Continuous Process

Implications for Dual-Process Theories of Recognition Memory

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ABSTRACT—*Dual-process theory, which holds that recognition decisions can be based on recollection or familiarity, has long seemed incompatible with signal detection theory, which holds that recognition decisions are based on a singular, continuous memory-strength variable. Formal dual-process models typically regard familiarity as a continuous process (i.e., familiarity comes in degrees), but they construe recollection as a categorical process (i.e., recollection either occurs or does not occur). A continuous process is characterized by a graded relationship between confidence and accuracy, whereas a categorical process is characterized by a binary relationship such that high confidence is associated with high accuracy but all lower degrees of confidence are associated with chance accuracy. Using a source-memory procedure, we found that the relationship between confidence and source-recollection accuracy was graded. Because recollection, like familiarity, is a continuous process, dual-process theory is more compatible with signal detection theory than previously thought.*

A long-standing theory holds that recognition memory decisions are supported by two processes, namely, recollection and familiarity. The following anecdote, offered by Mandler (1980), describes a common experience that illustrates how these two processes sometimes unfold in real time:

> Consider seeing a man on a bus whom you are sure that you have seen before; you "know" him in that sense. Such a recognition is usually followed by a search process asking, in effect, Where could I know him from? Who is he? The search process generates likely contexts (Do I know him from work; is he a movie star, a TV commentator, the milkman?). Eventually the search may end with the insight, That's the butcher from the supermarket! (pp. 252–253)

The initial sense of familiarity refers to a memory signal pertaining to the item itself (based, perhaps, on its perceptual features), whereas the subsequent awareness of recollection refers to the retrieval of source information that is associated with that item. Familiarity is widely assumed to be a continuous process in the sense that it is experienced in degrees. Low degrees of familiarity are associated with low confidence and low accuracy, whereas high degrees of familiarity are associated with high confidence and high accuracy. By contrast, the recollection process is almost always thought to be categorical in that, theoretically, it either occurs (yielding high confidence and high accuracy) or does not occur.

For continuous processes, the notion of a *decision criterion* almost inescapably comes into play. Thus, for example, on a typical old/new recognition memory test, the participant's task is to distinguish between targets (e.g., words that were presented on a previous list) and lures (e.g., words that were not presented on a previous list). Although the targets are likely to be relatively familiar because of their recent appearance on a list, the lures are associated with some degree of familiarity as well. Thus, for a decision that is based on familiarity, a participant must decide *how much* familiarity is enough to decide that the item is old. In other words, the participant must set a criterion familiarity value.

An early dual-process model proposed by Atkinson and his colleagues envisioned two criteria for familiarity-based decisions (Atkinson & Juola, 1973, 1974). According to this model, if the degree of familiarity associated with a test item was strong enough to fall above a high criterion or weak enough to fall below a low criterion, then a familiarity-based decision would be made (old or new, respectively). If the degree of familiarity instead fell between the two criteria (i.e., if familiarity was of intermediate

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strength), then a retrieval search would be initiated. That search was assumed to either succeed (in which case the item was declared to be old) or fail (in which case it was declared to be new). Thus, in this model, recollection was construed as a categorical process—one that does not involve a decision criterion. Mandler (1980) also pointed out that a decision criterion plays a role in familiarity-based decisions, but again treated recollection as a categorical process that either succeeds or does not succeed. The same approach to recollection and familiarity is taken in studies that use the process-dissociation procedure to obtain quantitative estimates of recollection and familiarity (Jacoby, 1991). In computing those estimates, recollection is again considered to be a categorical process, whereas familiarity is assumed to be a continuous process that involves a decision criterion (Jacoby, Toth, & Yonelinas, 1993). Finally, Yonelinas (1994) proposed a model in which recollection was assumed to be a categorical process that always yields high confidence and does not involve a decision criterion, whereas familiarity was regarded as a continuous signal detection process that does involve a decision criterion.

A common feature of all of these dual-process models, in addition to the fact that they regard recollection as a categorical process, is that they assume that individual recognition decisions are based either on one process or on the other. That is, according to all of these models, old/new decisions about items that elicit recollection are based solely on recollection, whereas old/new decisions about items that do not elicit recollection are based solely on familiarity. This is a natural way to think if one begins with the assumption that recollection is categorical. That is, in the categorical view, the occurrence of recollection would yield high confidence that an item was previously encountered, thereby rendering unnecessary any consideration of familiarity. But when recollection fails completely, the only recourse would be to rely on familiarity.

An alternative view is that recollection and familiarity are both continuous processes that are aggregated into a memory-strength signal (Wixted, 2007). According to this account, both processes play a role in an old/new decision about an individual test item. The core difference between this model and all earlier dual-process models is its assumption that recollection is a continuous process (i.e., it comes in degrees), not a categorical process. If recollection were a continuous process (e.g., Dodson, Holland, & Shimamura, 1998; Johnson, Hashtroudi, & Lindsay, 1993), then high degrees of recollection would result in high confidence and high accuracy, but low degrees of recollection would result in low confidence and low accuracy. In that respect, recollection would be like familiarity. In other respects, however, the two processes would remain distinct. That is, according to this view, familiarity is a fast process that involves the retrieval of information about the item per se, whereas recollection is a slower process that involves the retrieval of associated contextual information. But because recollection is assumed to occur in graded fashion, any degree of recollection that happens to occur would add to the extant familiarity-based memory signal instead of usurping it.

The research we report in this article was concerned with differentiating between the categorical and continuous views of recollection. We investigated this issue by using a source-memory procedure (Johnson et al., 1993), which is commonly used to study the recollection process. In this procedure, some items on a list are associated with one source attribute (e.g., the color red), and others are associated with a different source attribute (e.g., the color blue). On a later recognition test, participants are presented with test items in a source-neutral fashion (e.g., in black) and asked to recollect the original source attribute (i.e., a binary decision between Source A and Source B). In this experiment, however, participants were instead asked to rate their confidence in the item's source using a 20-point scale, with 1 representing highest confidence in Source A (e.g., blue) and 20 representing highest confidence in Source B (e.g., red). In a test like this, the familiarity of the test item is not diagnostic of its source because the items from both sources recently appeared on the same study list.

The categorical and continuous views of recollection make contrasting predictions about the relationship between the confidence in a source decision and the accuracy of that decision. The categorical view of recollection predicts that the relationship will be a step function. For example, an all-or-none version of the categorical model predicts that accuracy will be high for ratings made with the highest confidence (i.e., for ratings of 1 or 20) and will be no better than chance for all other ratings. By contrast, the continuous view of recollection predicts that the relationship will fall off in graded fashion (i.e., accuracy will be highest for ratings of 1 or 20, next highest for ratings of 2 and 19, and so on).

In prior investigations into this issue, participants were first asked to make an old/new decision using a 6-point confidence scale and then asked for a source decision. Yonelinas (2001) reported that source accuracy was above chance only for old/new decisions that were made with the highest level of confidence (a pattern consistent with the categorical view of recollection), but Wixted (2007) reviewed results from several other studies showing that source recollection was above chance even for old/new decisions that were made with low and medium levels of confidence (a pattern consistent with the continuous view of recollection). In the present experiment, we tested the relationship between confidence and accuracy for the source decision itself to directly test the categorical and continuous accounts, and we used a 20-point scale to examine the relationship over a wide range of confidence.

METHOD

Participants

The participants were 91 college undergraduates, who were recruited from the experimental participants pool at the University of California, San Diego. They gave their informed consent according to the protocol of the university's institutional review board and received class credit for completing our experiment. All participants were fluent in English.

Stimuli

The word pool used consisted of 705 three- to seven-letter words extracted from the MRC Psycholinguistic Database (Coltheart, 1981). We randomly selected 300 of these words for testing. Instructions and stimuli were presented using E-Prime 1.1.4.1 (Psychology Software Tools, Inc., www.pstnet.com) scripts on a Dell Dimension 4550 desktop computer with a 17-in. monitor. A second pool of 1,018 words drawn from Gilhooly and Logie (1980) was used for testing 6 participants over an especially large number of trials.

Procedure

Two similar versions of the experiment were run. In one, the relevant source attribute was font color; in the other, it was screen location. We ran two versions because some neuroimaging evidence suggests that recollecting a feature of the item itself, such as its color, may differ from recollecting an extra-item detail, such as the item's location (Staresina & Davachi, 2006). Participants were informed that 100 words would be presented in red or blue (Version 1; $n = 49$) or at the top or bottom of the screen (Version 2; $n = 36$) for 2 s each, and they were advised that their memory for color (Version 1) or location (Version 2) would be tested after the entire list was presented. Participants first completed a brief practice session to ensure they understood the task. On the subsequent recognition test, items were presented one at a time in black (on a white background) at the center of the screen, and participants made a source decision (red or blue in Version 1, top or bottom in Version 2) using a 20-point rating scale. On this scale, 1 indicated 100% certainty that the item was presented in blue (or at the bottom of the screen), and 20 indicated 100% certainty that the item was presented in red (or at the top of the screen). Lesser degrees of certainty were indicated using less extreme numbers, with ratings of 10 and 11 indicating choices of blue or red (or bottom or top), respectively, made with complete uncertainty.

An additional 6 participants were tested more extensively in the color memory version of the experiment so that their individual confidence-accuracy functions could be examined. For these participants, a list of 100 words was presented in each of five sessions. The list in each session was unique, and the recognition test that followed each list involved 100 targets randomly intermixed with 100 lures.

RESULTS

In the color version of the task, overall source-recollection accuracy (67.1%) was significantly above chance, $t(48) = 13.1$, $p_{rep} > .99$. The question of most interest concerns the relationship between confidence and accuracy. The 20-point rating scale provided 10 levels of confidence in "blue" decisions (1 = highest confidence that the item had been presented in blue, 10 = lowest confidence) and 10 levels of confidence in "red" decisions (20 = highest confidence that the item had been presented in red, 11 = lowest confidence). Thus, for purposes of analysis, the 20-point rating scale was converted to a 10-point confidence scale in which a value of 1 corresponds to ratings of 10 and 11 (lowest confidence in "blue" and "red" decisions, respectively), a value of 2 corresponds to the next highest ratings (9 and 12), and so on up to a value of 10, which corresponds to the highest ratings (1 and 20). For each participant, recollection accuracy was computed for each level of confidence. As Figure 1 shows, accuracy was no better than chance for confidence ratings of 1 through 4, but it was marginally greater than chance for ratings of 5 and 6. Accuracy was higher still (and was significantly greater than chance) for ratings of 7, 8, and 9, and it was far above chance for ratings of 10. Accuracy for the highest level of confidence (10) significantly exceeded that for the next lowest level (9), $t(38) = 3.73$, $p_{rep} = .99$.

In the location version of the task, overall source-recollection accuracy (77.1%) was also significantly above chance, $t(35) = 11.4$, $p_{rep} > .99$. The accuracy scores for each level of confidence were more variable than on the color version of the task, so the 10-point confidence scale was reduced to a 5-point confidence scale by averaging together adjacent confidence levels. As Figure 2 shows, recollection again increased in continuous fashion as confidence increased. Performance was no better than chance for confidence levels of 1 and 2, but it was clearly greater than chance (falling at approximately 75% correct) for confidence levels of 3 and 4. Accuracy for the highest level of confidence (5) was just under 90% correct and significantly exceeded accuracy for the next lowest level (4), $t(32) = 2.94$, $p_{rep} = .96$.

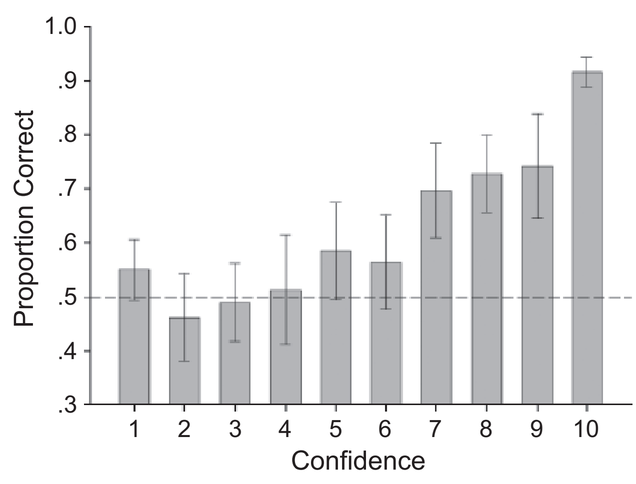

Fig. 1. Proportion correct as a function of confidence in the color version of the source-memory task. The error bars represent 95% confidence intervals.

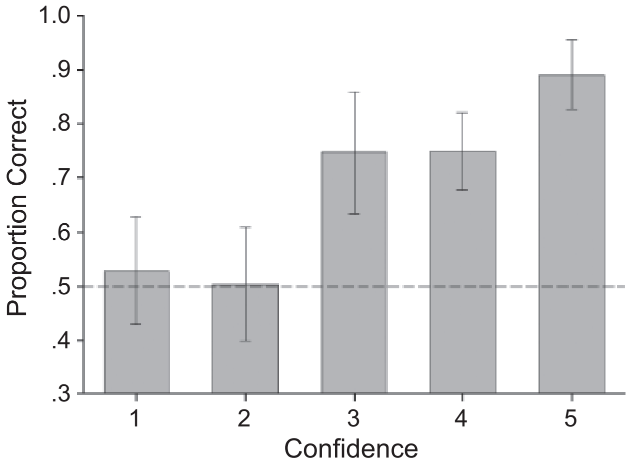

Fig. 2. Proportion correct as a function of confidence in the location version of the source-memory task. The error bars represent 95% confidence intervals.

The results shown in Figures 1 and 2 are inconsistent with a categorical view according to which recollection always yields the highest level of confidence. However, a different view of recollection might hold that although recollection is categorical, it does not always yield the highest level of confidence. That is, when recollection for Source A occurs, a participant might provide ratings between, say, 1 and 3, whereas when recollection for Source B occurs, the participant might provide ratings between 18 and 20. When these ratings are converted to a 10-point scale, a plot of the relationship between confidence and accuracy for a participant like this would reveal a step function, with accuracy for ratings of 8 through 10 being very high and all other ratings being associated with chance performance. If data from different participants yielded different categorical break points along the confidence rating scale, then averaging over participants would create the false impression of a continuous relationship.

To investigate this possibility, we also collected enough data from 6 participants to assess the confidence-accuracy relationship at the individual level (Fig. 3). If the confidence-accuracy plot is a step function, then the slope of a line fit through the possible below-threshold accuracy values should, on average, be zero, and accuracy for these values should be close to chance. Similarly, the slope of a line fit through the possible above-threshold values should also be zero, but at a level much greater than chance. Figure 3 shows accuracy as a function of confidence for each participant, using different shadings to distinguish between levels of confidence associated with possible below-threshold and above-threshold recollection. Also shown are straight lines that were separately fit to the presumptive below- and above-threshold data. No line could be fit to the single above-threshold value for Participant 2, whose overall pattern is clearly consistent with an all-or-none recollection model. However, of the remaining 11 sets of above- and below-threshold fits, all but 2 have positive slopes.

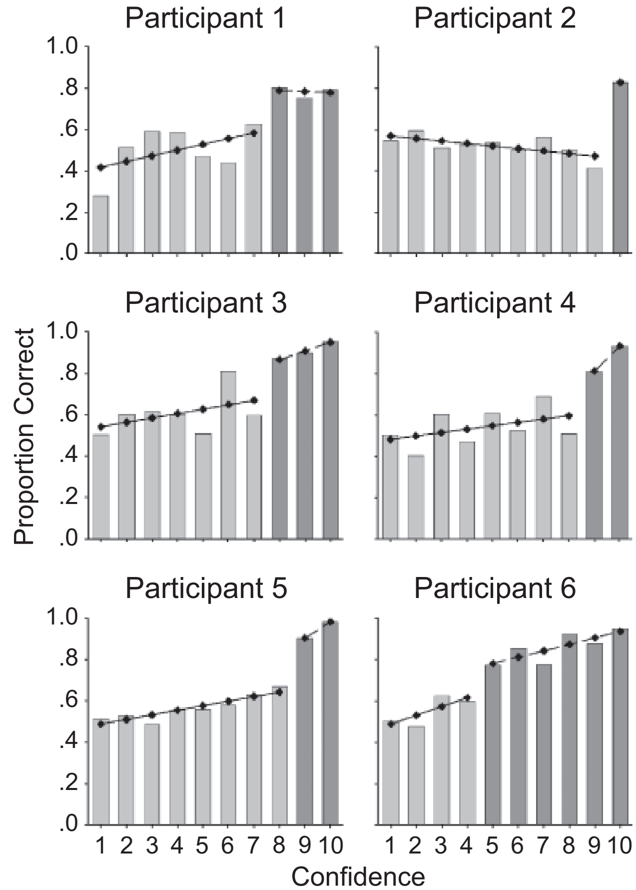

Fig. 3. Proportion correct as a function of confidence in the color version of the source-memory task for 6 individuals who were tested over a large number of trials. Confidence ratings associated with possible below-threshold recollection are indicated by light-gray bars, and confidence ratings associated with possible above-threshold recollection are indicated by dark-gray bars. The straight lines represent least squares fits to the presumptive below- and above-threshold data.

For each participant, the above-threshold and below-threshold slopes were averaged together (except for Participant 2, whose below-threshold slope was used) to obtain the most reliable slope estimate. The average slope was positive for 5 of the 6 participants (all participants except Participant 2) and was significantly greater than zero, $t(5) = 2.66$, $p_{rep} = .92$. The average slope remained significantly greater than zero when alternative break points were used (e.g., when the first above-threshold value was set to confidence level 7 for Participant 1, to 6 for Participant 3, or to 8 for Participant 6). Thus, although the data do not rule out the possibility that a subset of subjects experienced categorical recollection, the average plots of the relationship between confidence and accuracy shown in Figures 1 and 2 appear to be representative of the majority of individual participants.

Evidence for threshold recollection on source-memory tasks is often based on an analysis of the receiver-operating characteristic (ROC), which is commonly plotted in two ways. A standard ROC is a plot of the hit rate versus the false alarm rate associated with different levels of confidence, whereas a z-ROC is a plot of the z-transformed hit rate versus the z-transformed false alarm rate. A continuous signal detection model of recollection predicts a curvilinear ROC and a linear z-ROC, whereas a categorical recollection model instead predicts a linear ROC and a curvilinear z-ROC. For source-recollection tasks, the ROC is typically curvilinear, but the z-ROC is often curvilinear as well (Yonelinas & Parks, 2007). The curvilinearity of the z-ROC has been taken as evidence that recollection is a categorical process. Figure 4 shows the z-ROCs from both versions of this experiment, and they both exhibit the curvilinearity that is often seen on source-memory tasks. The curvilinearity is visually apparent and is also evident in the fact that the quadratic coefficients of the best-fitting second-order polynomials are positive (and equal to 0.20 in both cases). However, these z-ROCs are curvilinear even though recollection is a continuous process (as shown in Figs. 1 and 2), not because it is a categorical process. As we discuss later, this curvilinear anomaly does not seem to imply categorical recollection except insofar as memory can be so weak that, for some items, information about a particular source detail (such as the item's color or location during study) is completely absent.

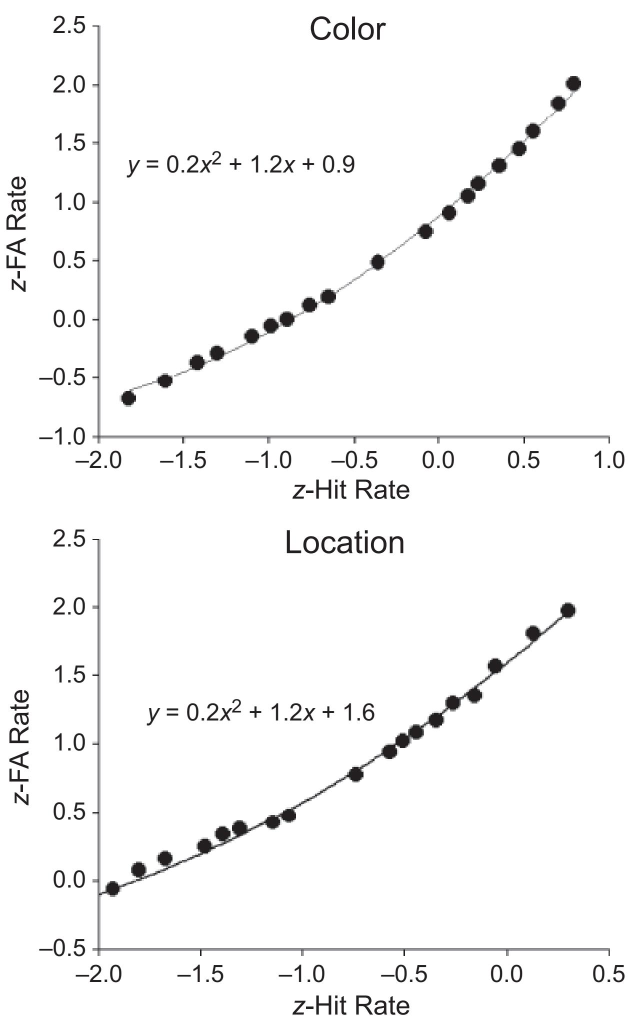

Fig. 4. Receiver-operating characteristic (ROC) plot of the z-transformed hit rate (z-Hit) versus the z-transformed false alarm rate (z-FA) for the color version of the task (upper panel) and location version of the task (lower panel). The smooth curve drawn through the z-ROC data in each plot represents the best-fitting second-order polynomial.

DISCUSSION

All of the major dual-process models of recognition memory hold that familiarity is a continuous process (one that involves a decision criterion), whereas recollection is a categorical process (one that does not involve a decision criterion). The results shown in Figures 1 and 2 suggest instead that recollection, like familiarity, is a continuous process. If recollection and familiarity are both continuous processes, then it stands to reason that the two processes jointly contribute to individual recognition decisions. In fact, unless they provided completely redundant information, an efficient memory system would (either by design or by learning) combine them to yield an aggregated memory-strength signal. Such an aggregated signal would be more diagnostic of prior occurrence than either signal alone.

The idea that individual recognition decisions are based on an aggregated memory-strength signal has potentially far-reaching implications. First, the traditional signal detection view of recognition memory involves two unequal-variance Gaussian distributions and a decision criterion (Fig. 5). This long-standing model—with its singular memory-strength axis—has been widely regarded as being at odds with the similarly long-standing dual-process model of recognition. However, if continuous recollection and familiarity signals are combined into a memory-strength variable, then these two venerable models are naturally reconciled (Wixted, 2007). This view implies that a decision criterion is just as relevant to the recollection process as it is to the familiarity process.

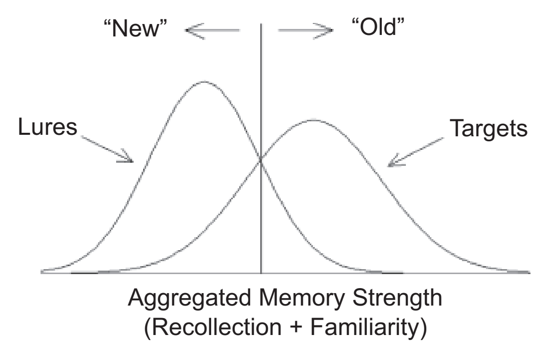

Fig. 5. Illustration of the standard unequal-variance signal detection model of recognition memory. In this particular version of the model, memory strength is construed as a continuous, unidimensional variable that is a joint function of recollection and familiarity. The distribution of memory-strength values associated with the targets has a higher mean and variance than the distribution of memory-strength values associated with the lures. Any test item that has a memory-strength value higher than the decision criterion is declared to be old; otherwise, it is declared to be new.

Second, much neuroimaging research aimed at identifying the neural correlates of recollection and familiarity is guided by dual-process models that implicitly or explicitly reject the signal detection model of recognition memory. That is, they are predicated on the assumption that individual recognition decisions are based either on categorical recollection or on continuous familiarity (never on both processes together). If that assumption is wrong, then the results of these studies need to be reinterpreted. For example, using a 6-point confidence scale (1 = *sure new*, 6 = *sure old*), Daselaar, Fleck, and Cabeza (2006) found that activity in the posterior hippocampus was similar for confidence ratings of 1 through 5, but was significantly elevated for confidence ratings of 6. On the basis of the assumption that recollection is a categorical all-or-none process that always yields the highest level of confidence, these authors concluded that the posterior half of the hippocampus selectively subserves the recollection process. But if recollection is a graded process such that varying degrees of recollection are associated with varying levels of confidence, then these results would instead suggest that activity in the posterior hippocampus is detectable when memory is strong, not when it selectively involves recollection (Squire, Wixted, & Clark, 2007). A similar reinterpretation would apply to many studies that have used confidence ratings or the related remember/know procedure to identify the neural correlates of recollection and familiarity (e.g., Eldridge, Knowlton, Furmanski, Bookheimer, & Engel, 2000; Montaldi, Spencer, Roberts, & Mayes, 2006; Vilberg & Rugg, 2007; Yonelinas, Otten, Shaw, & Rugg, 2005).

Because continuous memory processes are generally well characterized by signal detection theory, and because signal detection theory predicts a linear *z*-ROC, the curvilinear *z*-ROCs evident in Figure 4 (which are typical of source-memory procedures) seem to be unexpected in this view. A model that assumes recollection is a categorical high-confidence-or-none process predicts a curvilinear *z*-ROC, and the frequent occurrence of that pattern has often been taken to support the threshold recollection model (e.g., Yonelinas & Parks, 2007). However, the evidence summarized in Figures 1 and 2, which show that recollection is a continuous process, suggests that some other explanation applies. Indeed, recent work on the shape of source-memory ROCs has provided that explanation. Specifically, Slotnick and Dodson (2005) showed that the curvilinear shape of the source-memory *z*-ROC is a consequence of the fact that for items with weak old/new memory (i.e., for decisions made with low levels of old/new confidence), source information is absent. The standard signal detection model of source memory includes no provisions for items like these (i.e., items for which no degree of source information is available), so the prediction of a linear *z*-ROC does not apply when such items are included in the analysis. When they were excluded from the source ROC analysis, the shape of the ROC was consistent with the predictions of signal detection theory (Slotnick & Dodson, 2005). Critically, this was true even though all strong recollection-based decisions (i.e., all old/new decisions made with high confidence) remained in the source ROC analysis. Slotnick and Dodson's analysis shows that recollection-based ROCs are fully compatible with signal detection theory and that the curvilinear *z*-ROC often found with source-memory procedures arises because of the inclusion of weak items with no source memory, not because recollection is a threshold process whose occurrence always yields high confidence.

Finally, despite the common assumption that source-memory procedures tap recollection, it could be argued that the continuous relationship between confidence and accuracy means that source decisions are based on familiarity. For example, it could be argued that, at test, participants rely on a generate-recognize strategy by mentally simulating each test item, first as originating from Source A (e.g., in red) and then as originating from Source B (e.g., in blue). To make a decision, they might choose the imagined source that yields the higher feeling of familiarity. Although generate-recognize theory has been mostly abandoned as an explanation of recall (e.g., Tulving & Thompson, 1973), its possible role in source-memory tasks has not been ruled out. If source-memory decisions are based on familiarity, then neuroimaging studies that rely on source-memory procedures to study the neural correlates of recollection would need to be reconsidered. Moreover, the curvilinear *z*-ROCs obtained with such procedures (e.g., see Fig. 4), which are often attributed to categorical recollection, would also need to be explained in some other way (e.g., as being based on a combination of continuous source familiarity and categorical source recollection).

The most parsimonious interpretation of the present results is that recollection is a continuous process, one that can be associated with low levels of confidence and accuracy (contrary to all prior dual-process accounts), as well as high levels of confidence and accuracy. It seems reasonable to suppose that recollection underlies the strongest possible memories (as all dual-process models would stipulate), but the key point of departure here is that recollection also plays a role in weaker memories. This interpretation is consistent with evidence from the remember/know procedure showing that "know" responses, which are often thought to reflect familiarity-based decisions made with high confidence, are instead associated with relatively low confidence and above-chance levels of source recollection (Wais, Mickes, & Wixted, 2008). It is also consistent with recent single-unit recording evidence suggesting that recollection and familiarity are summed by neurons in the hippocampus (Rutishauser, Schuman, & Mamelak, 2008) and with recent modeling evidence directly testing the idea that the memory signal for individual items is based on both recollection and familiarity (Starns & Ratcliff, 2008). If recollection is a continuous process, and if the recollection and familiarity signals are aggregated into a unidimensional memory-strength variable, then dual-process theory and signal detection theory are naturally compatible accounts.

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