

The Two Recollections

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Recollection is currently modeled as a univariate retrieval process in which memory probes provoke conscious awareness of contextual details of earlier target presentations. However, that conception cannot explain why some manipulations that increase recollection in recognition experiments suppress false memory in false memory experiments, whereas others increase false memory. Such contrasting effects can be explained if recollection is bivariate—if memory probes can provoke conscious awareness of target items per se, separately from awareness of contextual details, with false memory being suppressed by the former but increased by the latter. Interestingly, these 2 conceptions of recollection have coexisted for some time in different segments of the memory literature. Independent support for the dual-recollection hypothesis is provided by some surprising effects that it predicts, such as release from recollection rejection, false persistence, negative relations between false alarm rates and target remember/know judgments, and recollection without remembering. We implemented the hypothesis in 3 bivariate recollection models, which differ in the degree to which recollection is treated as a discrete or a graded process: a pure multinomial model, a pure signal detection model, and a mixed multinomial/signal detection model. The models were applied to a large corpus of conjoint recognition data, with fits being satisfactory when both recollection processes were present and unsatisfactory when either was deleted. Factor analyses of the models' parameter spaces showed that target and context recollection never loaded on a common factor, and the 3 models converged on the same process loci for the effects of important experimental manipulations. Thus, a variety of results were consistent with bivariate recollection.

Keywords: target recollection, context recollection, false memory, conjoint recognition

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The retrieval process of recollection has been a topic of sustained theoretical development over the past several years. Two prominent examples of the advances that have been made are a series of theory-driven techniques for disentangling recollection's effects from those of familiarity (e.g., the dual process receiver-operating characteristic, the process-dissociation paradigm, and the remember/know paradigm) and a reconceptualization of recollection as a continuous rather than a discrete process (as in the sum-difference and continuous dual process models of remember/know judgments). With respect to those two advances alone, it would be possible to mention literally dozens of important contributions, but articles by Diana, Reder, Arndt, and Park (2006); Dunn (2008); Heathcote (2003); Malmberg (2008); Migo, Mayes, and Montaldi (2012); Rotello, Macmillan, and Reeder (2004); Wixted and Mickes (2010); and Yonelinas (2002) encompass most of the key issues. In the present article, we continue this line of

theoretical development by examining a core question that has not yet received either careful conceptual analysis or focused empirical study: Are there distinct forms of recollection?

The dominant assumption in the mainstream memory literature is that recollection is a univariate process that involves the retrieval of contextual details that were associated with target presentations. For instance, contemporary dual process models of recognition implement univariate conceptions of recollection—regardless of whether recollection and familiarity are modeled as discrete variables (e.g., Jacoby, 1991), recollection is modeled as discrete and familiarity as continuous (e.g., Yonelinas, 1994), or both are modeled as continuous (e.g., Rotello et al., 2004; Wixted & Mickes, 2010). We propose that recollection is actually bivariate, that there are two varieties that are difficult to distinguish when measuring memory for target presentations (true memory) but that can be separated and modeled by virtue of their contrasting effects on memory for distractors that preserve salient features of targets (false memory). The two forms of recollection for such items can be modeled as discrete or as continuous variables.

In the course of this article, we consider several findings that motivate the hypothesis that there are distinct forms of recollection. However, for us, this hypothesis was first motivated by anomalous findings on how recollection is connected to the accuracy of episodic memory reports. That connection is one of recollection's most notable properties, and it figured in the earliest work on this process by Strong (1913). Strong's subjects introspected on mental events that coincided with hits and false alarms

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on recognition tests. They often reported that test words that were accepted as old consciously reinstated vivid reactions that those words had provoked when they were presented on study lists (e.g., visual images, emotions, thoughts, associations to related words). Such reports were made chiefly about words that had in fact been presented—more particularly, the great preponderance of those reports were made for hits rather than false alarms, and in relative terms, they were common for hits but uncommon for false alarms. All of this suggests that recollection redounds to the benefit of accuracy. More recent evidence of a recollection–accuracy relation can be found in reviews of research using the preeminent method of measuring recollective retrieval, remember (R) judgments in Tulving's (1985) remember/know (R/K) paradigm. For example, in an early review, Donaldson (1996) analyzed 80 sets of R/K data. R judgments occurred overwhelmingly for hits rather than false alarms (93% vs. 7%), and in relative terms, they were the predominant basis for hits (65% were followed by R judgments) but not for false alarms (25% were followed by R judgments).

The assumption that recollection redounds to the benefit of accuracy because it strongly discriminates presented from unrepresented material has figured centrally in the false memory literature. There, it has prompted the hypothesis that errors to the customary false memory items can be reduced by manipulations that elevate recollective support for targets (Brainerd, Reyna, Wright, & Mojardin, 2003) and that such manipulations can even induce metacognitive expectations that targets but not distractors will retrieve recollective support (Strack & Bless, 1994). When the literature is examined in light of this hypothesis, however, there are conflicting results. If manipulations are considered whose ability to elevate R judgments for targets is well established, some have indeed been found to reduce false memories, but others have been found to increase false memories.

We survey such conflicting results in the first section of the present article. In the second section, they are explained with a dual-recollection hypothesis. There, we discuss a variety of theoretical and empirical evidence converging on the notion that there are two forms of recollection, which are termed target and context recollection. We show that the procedure that produces the conflicting results, the R/K paradigm, explicitly authorizes subjects to use either form as a basis for reporting recollective support. We also show that Tulving's (1985) original focus was on target recollection and that this focus was broadened by subsequent investigators to include context recollection. In the third section, we review four independent lines of empirical evidence for dual recollection: release from recollection rejection, false persistence, negative correlations between false alarms and true R judgments, and recollection without remembering.

In the fourth section, the dual-recollection principle is implemented in three models that are defined over the distractor data of conjoint recognition designs: (a) a pure multinomial model in which target recollection, context recollection, and familiarity are all discrete variables; (b) a mixed multinomial/signal detection model in which target recollection is discrete while context recollection and familiarity are continuous; and (c) a pure signal detection model in which all three processes are continuous. The availability of these three models makes experimental findings less dependent upon a priori assumptions about which processes are discrete and which are continuous because by applying them in tandem, one can assess the extent to which they yield convergent

results. That is done in the fifth section of the article, where the models are applied to a large corpus of conjoint recognition data. It is shown that the models generate convergent findings with respect to fit, the values of their respective parameter estimates, the factor structure of their parameter spaces, the process loci of the effects of manipulations, and the relative contributions of target recollection, context recollection, and familiarity to performance. In the sixth section, the three models are extended to include dual-recollection processes for target data as well as distractor data. It is shown that these extended models generate the same convergent findings as the distractor models.

An Empirical Puzzle

As mentioned, a familiar idea in the false memory literature is that increasing the tendency of target probes to retrieve recollective support will reduce errors to the customary false memory items. Here and in the remainder of this section, we refer to results from one of the main paradigms in that literature, simple false memory for occurrence. In this paradigm, subjects are exposed to some memory targets (e.g., *couch* and *auto* are presented as part of a word list), followed by a memory test on which recognition/recall of distractors that preserve salient properties of targets (*sofa*, *car*) is the index of false memory.

Various mechanisms have been proposed whereby the ability of target items to retrieve recollective support could suppress false memories, ranging from processes that operate at the level of individual targets to processes that operate at a metacognitive level (Brainerd & Reyna, 2005; Gallo, 2004; Schacter, Israel, & Racine, 1999). Upon first impression, there seems to be ample experimental confirmation that false memories decline as targets' tendency to retrieve recollective support increases. Extensive evidence comes from studies in which false memory was measured under conditions that have been found, in prior R/K experiments, to elevate target R judgments. Naturally, there are procedures other than R/K that can be used to measure how different conditions affect recollection, such as process dissociation (Jacoby, 1991), receiver-operating characteristic (ROC) curves (Yonelinas, 1994), rating the phenomenological qualities of memories (Johnson, Foley, Suengas, & Raye, 1988), and still other techniques. However, the R/K literature dwarfs those for all other paradigms combined (for reviews of parts of it, see Dunn, 2008; Gardiner & Richardson-Klavehn, 2000; Rotello et al., 2004), and importantly, it contains several manipulations for which R/K data are so plentiful that their ability to increase recollective retrieval (R judgments) is not in doubt.

Many of those same manipulations have been found to suppress errors to related distractors in false memory experiments. To illustrate, consider five manipulations that increase the frequency of target R judgments in simple recognition designs: replacing word lists with picture lists (e.g., Wagner, Gabrieli, & Verfaellie, 1997), increasing the number of presentations per target (e.g., Dewhurst & Hitch, 1997), decreasing list length (e.g., Rajaram, 1993), decreasing target frequency (e.g., Guttentag & Carroll, 1997), and testing younger versus older adults (e.g., Duarte, Graham, & Henson, 2010). In false memory experiments, as expected, all of these manipulations have been found to reduce false memory levels (e.g., Brainerd, Payne, Wright, & Reyna, 2003; Duarte et al.,

2010; Gallo & Roediger, 2003; Goz, 2005; Schacter et al., 1999; Sugrue & Hayne, 2006).

However, suppose it is also possible for increases in target recollection to be inimical to accuracy, that enhancing recollective support for targets can also increase error rates for related distractors. Surprisingly, there is much evidence in favor of this possibility, too. To illustrate, consider five other manipulations that increase the frequency of target R judgments in simple recognition designs: generating rather than reading targets (e.g., Hicks, Marsh, & Ritschel, 2002), studying targets under longer versus shorter exposure times (e.g., Hirshman, Fisher, Henthorn, Arndt, & Passannante, 2002), studying emotionally valenced targets rather than neutral ones (e.g., Ochsner, 2000), studying targets under full rather than divided attention (e.g., Mangels, Picton, & Craik, 2001), and studying targets under deep rather than shallow encoding instructions (e.g., Lindsay & Kelley, 1996). In false memory experiments, all of these manipulations have been found to increase false memory levels (e.g., Abadie, Waroquier, & Terrier, 2013; Dewhurst, Bould, Knott, & Thorley, 2009; Howe, Candel, Otgaar, Malone, & Wimmer, 2010; Seamon, Luo, & Gallo, 1998; Toglia, Neuschatz, & Goodwin, 1999).

To complicate matters further, the rule that subjects rarely report recollective support when they falsely accept distractors does not always hold either. Lampinen, Neuschatz, and Payne (1998) first drew attention to this fact in an early review of the false memory literature, and it is also the focus of a recent review by Arndt (2012). There is an extensive array of procedures that produce statistically reliable levels of recall/recognition of unrepresented information (see Brainerd & Reyna, 2005). Lampinen et al. observed that some of them (e.g., Bransford, Barclay, & Franks, 1972) also produce high levels of ersatz recollective support for false memories—often called phantom recollection to distinguish it from recollective support for true memories. More explicitly, reports of specific visual, auditory, and cognitive details from the study phase usually accompany false memories in these paradigms (e.g., Lampinen, Meier, Arnal, & Leding, 2005; Payne, Elie, Blackwell, & Neuschatz, 1996). Furthermore, experimentation on this phenomenon has converged on the important conclusion that on memory tests, related distractors (e.g., *sofa*, *car*) directly retrieve the same contextual details that their corresponding targets (e.g., *couch*, *auto*) retrieve. Arndt explored this issue in depth. He pointed out that control procedures have been devised for paradigms that generate high baseline levels of phantom recollection, in which reports of recollective support for false memories must be based on direct retrieval of specific study-phase details by false memory items, rather than on inferences from target memories (e.g., Hicks & Hancock, 2002; Hicks & Starns, 2006). As Arndt noted, high levels of ersatz recollective support for false memories persist when those procedures are applied. Overall, the literature on this topic shows that on memory tests, distractors that share salient features of targets are able to retrieve contextual details that were associated with those targets' presentations; that when feature overlap is high, distractors can retrieve such details at rates that approach those for targets (Lampinen, Meier, et al., 2005); and that retrieval of such details supports subjectively compelling false memories.

Dual Recollection

The fact that manipulations that increase targets' tendency to retrieve recollective support sometimes suppress but sometimes foment false memories can be explained on the ground that there are two varieties of recollection. Before that explanation is considered, we discuss two pertinent background facts—namely, that these different varieties of recollection have coexisted in the memory literature for some time and that the instructions that subjects receive in R/K experiments actually authorize them to use both as bases for R judgments. Second, we show how the two recollections explain the finding that some manipulations that increase target R judgments lower false memories, whereas others increase them. Then, in the next section of this article, we review additional findings that provide independent evidence for that explanation.

Context Recollection and Target Recollection

Roughly speaking, the two conceptions of recollection are memory analogues of the figure–ground and part–whole distinctions in perception, where it is well established that figure–whole information is processed and represented differently than ground–part information (for a recent review, see Wagemans et al., 2012). One conception is dominant in the contemporary recognition literature, while the other has been widely discussed in the false memory literature. The dominant notion in the recognition literature, context recollection, focuses on conscious reinstatement of ground–part information from study events. For instance, the appearance of *flute* on a study list might provoke subjective generation of a few notes of a favorite overture, and its subsequent appearance on a recognition test may cue conscious reinstatement of that experience. We have seen that this type of recollection can be traced to Strong (1913), who emphasized awareness of details that accompanied target presentations, especially subjectively generated ones, rather than awareness of target presentations themselves. Recollection was also characterized as conscious reinstatement of contextual details in Mandler's (1980) influential article. Currently, this characterization prevails in recognition research, where recollection is variously defined as “retrieving specific details associated with the prior presentation of an item” (Wixted, 2007, p. 152), “conscious recollection of any details about the experience” (Rotello et al., 2004, p. 589), and “conscious memory for contextual or episodic details of prior events” (Parks, Murray, Elfman, & Yonelinas, 2011, p. 862). Note the absence of conscious awareness of the targets themselves in these formulations. Standard examples of contextual details are (a) features of the laboratory room and apparatus; (b) appearance, color, size, and position of visual presentations; (c) gender, accent, and loudness of auditory presentations; and (d) a range of uncontrolled subjective information that subjects generate as targets are presented (e.g., associations and inferences, emotional responses, visual and auditory images, somatic responses).

The other conception of recollection, which is prevalent in false memory research, stresses conscious reinstatement of figure–whole information from study events, that is, targets per se as distinct from accompanying contextual details. This notion was adopted in Tulving's (1985) original article on the R/K paradigm, where it was attributed to Ebbinghaus (1885), and it can be traced to an earlier analysis of false recognition of related distractors (Tulving, 1983). Although no amount of retrieved contextual detail

suffices to identify such probes as distractors (actually, the data indicate that these details lead subjects to regard them as targets; Arndt, 2012; Lampinen, Meier, et al., 2005), Tulving proposed that if subjects can clearly recollect the presentation of the corresponding target when such a probe is presented as a retrieval cue, then “the rememberer can decide not to call the retrieval cue ‘old’ even if it looks ‘familiar’” (Tulving, 1983, p. 317). The core idea is that target recollection generates feelings of contrast between a target whose presentation is clearly remembered and a distractor that resembles it but plainly mismatches it. Similarly, in Tulving’s R/K article, subjects were said to have autoecic awareness of a target and were instructed to make an R judgment if “they actually ‘remembered’ its occurrence in the list” (Tulving, 1985, p. 8). There is no mention at all of contextual details as a basis for either autoecic awareness or R judgments, and Tulving even reported an experiment in which test conditions that primed contextual details (two types of cued recall) produced *lower* levels of R than a condition that did not (free recall).

Nowadays, the target recollection idea is central to fuzzy-trace theory’s account of false memory (Brainerd & Reyna, 2005). In the false memory literature, typical characterizations of target recollection are “conscious remembrance of the occurrence of that probe on the study list” (Brainerd, Wright, Reyna, & Mojardin, 2001, p. 307), “conscious recollection of the word from the list” (Miller & Wolford, 1999, p. 399), and the ability to “consciously recollect the presentation of its instantiating target” (Lampinen, Meier, et al., 2005, p. 955). Note the absence of conscious awareness of accompanying contextual details in these formulations.

Consistent with Tulving’s (1983) original proposals, such formulations have most often appeared in connection with a false memory suppression process that is variously termed recollection rejection (e.g., Brainerd, Reyna, et al., 2003) or recall-to-reject (e.g., Lampinen, Odegard, & Neuschatz, 2004). The central assumption is that clear remembrance of the presentation of the target itself, as opposed to accompanying contextual details, leads to affirmative rejection of physically or semantically related distractors by neutralizing their high levels of familiarity: “a person . . . may mistakenly recognize the word ‘Dog’ on a test list. This error can be avoided, however, if one consciously recollects the study item at time of test (e.g., ‘I know it wasn’t ‘dog’, it was ‘puppy’.’)” (Lampinen & Odegard, 2006, p. 652) and

the subject might have thought that both *table* and *chair* could have been in the study list. . . if they were able to clearly recall *table*, but *chair* was only vaguely familiar, then they might reason that *chair* probably was not studied. (Gallo, 2004, p. 121)

This target form of recollection seems to be essential for rejecting distractors whose surface structure and meaning are virtually the same as targets’ (e.g., *computer* vs. *computers*, *lexib* vs. *lexid*, or *book-pie* vs. *pie-book*), which subjects are certainly able to do because false alarm rates for such distractors are lower than hit rates (e.g., Brainerd, Stein, & Reyna, 1998; Lampinen et al., 2004; Rotello, 2000).¹

The foregoing definitions of target and context recollection do not rule out the possibility that the two always occur concurrently. If recollection is truly bivariate, however, subjects must sometimes be consciously aware of studying specific targets without being aware of accompanying contextual details, and conversely. In that connection,

the memory literature supplies demonstrations of both target-recollection-without-context-recollection and context-recollection-without-target-recollection.

Recall seems to provide rather unambiguous demonstrations of target-recollection-without-context-recollection. They come from experiments in which subjects study some material, respond to a recall test, and are then unable to remember contextual details that accompanied the specific targets that were just recalled (Mickes, Seale-Carlisle, & Wixted, 2013). Target recollection is presumably being experienced because these items were just read out of consciousness, but nevertheless, context recollection is unsuccessful for a sizeable percentage. Mickes et al. (2013) reported such findings for young adults. Their subjects recalled word lists and then made source judgments about recalled items, with source memory being inaccurate for 37% of recalled items. Some years earlier, Shimamura and Squire (1987) reported a related clinical phenomenon, which they called source amnesia. Patients with amnesia that was mostly pursuant to Korsakoff’s syndrome and a sample of alcoholic control subjects learned a series of unfamiliar facts (e.g., Angel Falls is located in Venezuela) and received a subsequent recall test. For facts that were recalled, subjects responded to a source test that asked when they had last encountered them, with amnesic patients’ source memory being inaccurate for 45% of the facts.

Gomes (2014) reported further data on target-recollection-without-context-recollection in recall that mapped failures of context recollection with independent measures of target recollection. Although, intuitively, recall involves target recollection, it has been proposed that some portion of it actually relies on nonrecollective processes such as reconstruction (Brainerd, Reyna, & Howe, 2009) or familiarity (Mickes et al., 2013). To allow for that possibility, Gomes used the dual-retrieval model of recall to obtain independent estimates of recollective and nonrecollective retrieval for individual targets. For recalled items, subjects made source judgments about contextual details that had accompanied their presentation, similar to Mickes et al. (2013). Source memory was inaccurate 37% of the time, again similar to Mickes et al. The key new finding was that those inaccuracies occurred when items were retrieved recollectively (i.e., target-recollection-without-context-recollection) as well as nonrecollectively. Indeed, there was no correlation between source accuracy and whether retrieval was recollective or nonrecollective, both when recollective retrieval was measured within subjects (pooling over items) and when it was measured within items (pooling over subjects).

Turning to context-recollection-without-target-recollection, we know that the subjects in false memory for occurrence experiments often falsely recall/recognize distractors that preserve salient fea-

¹ These statements should not be interpreted to suggest that target recollection is the only way in which subjects suppress false memories to related distractors. For example, other types of suppression mechanisms have been described in a theory developed by Gallo (2004, 2013). Gallo distinguished between a type of suppression that relies on recollective information to set an overall decision criterion for targets and distractors (diagnostic monitoring) and a type that relies on metacognitive information (disqualifying monitoring) to rule out classes of probes that could not have been presented. Here, our intent is not to present an analysis of false memory suppression but merely to exemplify a property of target recollection that can be used to develop models that disentangle it from context recollection (see the section Conjoint Recollection, below).

tures of targets (e.g., Tussing & Greene, 1999). R/K tasks have been administered as part of the memory tests in some of these experiments (e.g., Roediger & McDermott, 1995), and it has been found that the phenomenology that is associated with such false memories is frequently reported as R rather than K. These responses are examples of context-recollection-without-target-recollection because, on the one hand, subjects are reporting recollective phenomenology (R judgments), but on the other hand, they cannot be recollecting the events' prior presentations because distractors were not presented. Direct support for that interpretation comes from experiments in which subjects are asked to report contextual details that accompanied the "presentation" of distractors (e.g., Payne et al., 1996). Subjects routinely report specific study-phase details, most commonly details that accompanied presentations of distractors' corresponding targets (Arndt, 2012).

Finally, the distinction between target and context recollection should not be confused with another important distinction—namely, criterial versus noncriterial recollection (e.g., Gallo, 2013; Ingram, Mickes, & Wixted, 2012). The contextual details that are associated with the presentation of targets can be partitioned into ones that are irrelevant to a memory task (e.g., in a source task, details that accompany all targets, such as features of the laboratory room and apparatus, the time of day) versus ones that are relevant (e.g., details that accompany only certain targets, such as words pronounced in a male voice vs. a female voice). On memory tests, conscious awareness of the latter (e.g., that *auto* was pronounced in a male voice or that *couch* was pronounced in a female voice) is termed criterial recollection, and conscious awareness of the former is termed noncriterial recollection. Whereas current formulations of context recollection emphasize the quantity of recollected details (see Dual-Recollection Models, below), the criterial–noncriterial distinction emphasizes their quality. It has been found that some criterial details (e.g., pictures) are easier to recollect than others (e.g., font, color) and that this can increase subjects' reliance on diagnostic monitoring in false memory experiments (Gallo, 2013). Specifically, when subjects are told to accept only targets whose accompanying contextual details are ones that they know are distinctive (e.g., pictures), they are less apt to falsely accept other targets than when they are told to accept only targets whose accompanying contextual details are known to be less distinctive.

The criterial–noncriterial distinction differs from the target–context recollection distinction in two key respects. First, it is focused squarely on the context side of recollection. Second, as mentioned earlier, the consequences for false memory of recollecting contextual details are different than the consequences of target recollection. Target recollection suppresses false alarms to related distractors, but when related distractors retrieve contextual details, whether criterial or noncriterial, this supports false alarms (Lampinen, Meier, et al., 2005). Studies of false memories that are supported by retrieval of criterial details, in particular, are featured in Arndt's (2012) review. In the typical experiment (e.g., Hicks, & Starns, 2006; Payne et al., 1996), subjects study a word list that is subdivided into blocks of semantically related words (e.g., medical terms, furniture names, dessert names, and insect names) that are accompanied by criterial contextual details (e.g., medical terms and dessert names are pronounced in a male voice, but furniture and insect names are pronounced in a female voice). Suppose that *doctor* was not presented in the medical block and *chair* was not

presented in the furniture block. When these items appear on memory tests, false alarms to *doctor* are often accompanied by recollection of the criterial detail for medical terms, whereas false alarms to *chair* are often accompanied by recollection of the criterial detail for furniture names.

Target Recollection, Context Recollection, and False Memory

It is not difficult to see that the dual-recollection hypothesis explains the anomalous effects that increasing target R judgments have on false memory, with one proviso: that subjects are using both types of recollection as a basis for such judgments, so that they can be increased by different routes—one that supports false memory (context recollection) and one that suppresses it (target recollection). Of course, R judgments have often been criticized as impure measures of recollection, and there is continuing disagreement as to whether the R/K paradigm actually measures distinct recollection and familiarity processes (e.g., compare Rotello et al., 2004, to Dunn, 2008, to Wixted & Mickes, 2010). The traditional claim about R judgments is that they are contaminated by familiarity (e.g., Heathcote, Bora, & Freeman, 2010; Malmberg, 2008). The claim here is that R judgments are contaminated in two ways—in the traditional sense of being mixed measures of recollection and familiarity but also in the sense of being mixed measures of target and context recollection. With respect to the latter proposal, the conventional view in the R/K literature is that the type of recollective phenomenology that R judgments tap is conscious awareness of study-phase contextual details. Yet close inspection of the instructions that have long been administered in R/K experiments reveals that while they authorize subjects to base R judgments on context recollection, they also authorize subjects to base R judgments on target recollection.

To begin, remember that context recollection did not figure at all in Tulving's (1985) original conception and that, instead, he instructed subjects to base R judgments on target recollection. The emphasis on contextual details emerged later, first in an article by Gardiner and Java (1990) and then in a very influential article by Rajaram (1993). In an initial follow-up of Tulving (1985), Gardiner (1988) implemented Tulving's original instructions, asking subjects to make an R judgment about an item when "they were able consciously to recollect its prior occurrence in the study list" (p. 310). Gardner and Java's instructions, which appear at the top of Table 1, shifted the emphasis in the direction of context recollection. It can be seen that conscious awareness of a target's prior presentation still counts as a basis for R but so do "aspects of the previous experience," and conversely, lacking conscious awareness of anything "about its occurrence or what we experienced at the time" is the basis for K (Gardiner & Java, 1990, p. 25). However, Gardiner and Java's instructions supply no examples of typical contextual details that subjects might rely on. That was the key innovation of Rajaram's instructions, which have been adopted in the bulk of subsequent R/K experiments. Those instructions appear at the bottom of Table 1, where two points merit attention. First, subjects are provided with concrete examples of contextual details that may be used as a basis for R judgments. Second, subjects are still told that target recollection may be used as a basis for R judgments. Reading through the instructions, it is clear that an R judgment is authorized if a probe provokes con-

Table 1
Examples of Remember/Know Instructions

Study	Instructions
Gardiner & Java (1990, p. 25)	Often, when <i>remembering</i> a previous event or occurrence, we consciously recollect and become aware of aspects of the previous experience. At other times, we simply know that something has occurred before, but without being able consciously to recollect anything about its occurrence or what we experienced at the time. Thus in addition to your indicating your recognition of a word from the original study set, I would like you to write either the letter "R" after the encircled item, to show that you recollect the word consciously, or "K" if you feel you simply know that the word was in the previous study set. So, for each word that you recognize, please write "R" next to it if you recollect its occurrence, or "K" if you simply know that it was shown on the cards.
Rajaram (1993, p. 102)	Remember judgments: If your recognition of the word is accompanied by a conscious recollection of its prior occurrence in the study list, then write "R." "Remember" is the ability to become consciously aware again of some aspect or aspects of what happened or what was experienced at the time the word was presented (e.g., aspects of the physical appearance of the word, or of something that happened in the room, or of what you were thinking and doing at the time). In other words, the "remembered" word should bring back to mind a particular association, image, or something more personal from the time of study, or something about its appearance or position (i.e., what came before or after that word). Know judgments: "Know" responses should be made when you recognize that the word was in the study list but you cannot consciously recollect anything about its actual occurrence or what happened or what was experienced at the time of its occurrence. In other words, write "K" (for "know") when you are certain of recognizing the words but these words fail to evoke any specific conscious recollection from the study list. To further clarify the difference between these two judgments (i.e., "R" vs. "K"), here are a few examples. If someone asks for your name, you would typically respond in the "know" sense without becoming consciously aware of anything about a particular event or experience; however, when asked the last movie you saw, you would typically respond in the "remember" sense, that is, becoming consciously aware again of some aspects of the experience. If you have any questions regarding these judgments, please ask the experimenter.

scious awareness of its prior occurrence or conscious awareness of some physical or psychological detail that happened at the time.

Summing up, our proposal that R judgments are mixed measures of the two forms of recollection is not predicated on complex measurement arguments or subtle reinterpretations of data. It merely reflects the current operational definition of such judgments. Thus, the fact that manipulations that elevate them can have opposite effects on false memory is explicable, based on how the two forms of recollection are treated in the false memory literature, where target recollection has been tied to false memory rejection (Belli, 1993; Brainerd, Reyna, et al., 2003) and context recollection has been tied to false memory acceptance (Arndt, 2012; Lampinen, Meier, et al., 2005; Payne et al., 1996).

Further Evidence for Dual Recollection

Although the dual-recollection hypothesis can account for puzzling findings, empirical support that goes beyond *ex post facto* explanation is desirable. Below, we sketch four such lines of evidence, each of which is focused on a different prediction of the hypothesis. The first two are phenomena on which extensive data can be found in the false memory literature: release from recollection rejection (e.g., Brainerd & Reyna, 2002) and false persistence (e.g., Toglia et al., 1999). The third is a negative relation between target R judgments and false memory that we detected in a corpus of R/K data sets that were culled from the false memory literature. The last is the mirror image of the aforementioned phenomenon of being able to recall studied targets without being able to recollect accompanying contextual details—namely, being able to recollect the accompanying contextual details without being able to remember the targets themselves, which demon-

strates that recollection in the context sense does not guarantee recollection in the target sense and, indeed, is independent of it.

Release From Recollection Rejection

Consider, again, the simple false memory for occurrence paradigm, so called because the error lies merely in thinking that certain events occurred that in fact did not. The events in question are ones that preserve salient features of targets, and hence, false recognition/recall of related distractors is the false memory measure. In the most common type of experiment, subjects study a series of targets (*couch, auto, . . .*), and then, they respond to a recognition test composed of three types of probes: targets, related distractors (*sofa, car, . . .*), and unrelated distractors (*teacher, bird, . . .*). Their task is simply to accept targets and reject distractors. Subjects are instructed that some distractors will seem quite familiar because they preserve salient properties of targets, so that those probes can be rejected if the corresponding target presentations are clearly remembered. Thus, target recollection generates the contrast/mismatch phenomenology described in fuzzy-trace theory, supporting affirmative rejection of related distractors. However, such probes may also retrieve specific contextual details from the study phase, generating identity/match phenomenology for related distractors and supporting false alarms. When related distractors fail to provoke either form of recollection, they may of course be accepted on the basis of familiarity.

The first effect falls out of the fact that the two recollections have opposite effects on acceptance rates for related distractors. Brainerd and Reyna (2002) noted that if subjects use target recollection to suppress false acceptance of related distractors, a simple instructional manipulation, in which a second group of subjects is

told that related distractors but not unrelated ones can also be accepted, ought to produce the following pattern: Relative to the standard old/new condition, acceptance rates for related distractors should rise because target recollection, as well as context recollection and familiarity, can now be used as a basis for acceptance.

Confirmatory data can be found in several experiments in which old/new recognition was pitted against instructions specifying that both targets and related distractors should be accepted (often called gist or meaning recognition; Koutstaal, 2003). These experiments cover a range of target materials (e.g., words, pictures, narratives, live events), target–distractor relations (e.g., category membership, synonymy, visual similarity, phonological similarity), and subject samples (children, adolescents, young adults, older adults). The four panels of Figure 1 show illustrative data from articles by Koutstaal (2003) on false memory for pictures from the same taxonomic categories as targets, by Brainerd and Reyna (1998) on false memory for words that are semantic associates of targets, by Singer and Remillard (2008) on false memory for sentences that are paraphrases of targets, and by Odegard and Lampinen (2005) on false memory for words that are antonyms or rhymes of targets. In each panel, the acceptance rates for related distractors under old/new and gist instructions are plotted. The dominant pattern across these data sets is the predicted one. Acceptance rates for related distractors are higher under gist instructions than old/new instructions, the average increase in the various data sets in Figure 1 being from .26 to .47.

Thus, subjects seem to use memory for the presentation of specific targets to suppress false memory for related distractors under old/new instructions. Remember, here, that the only differ-

ence between the two instructional conditions lies in whether such memories should be used to reject or accept related distractors. Furthermore, data like those in Figure 1 cannot be explained by assuming that subjects adopt more liberal decision criteria under gist instructions because the plotted data were corrected for differences in decision criteria. Acceptance probabilities were corrected using a two-high-threshold bias adjustment. Other standard methods of equating for differences in decision criteria (e.g., plotting d' values) yielded the same qualitative picture as Figure 1.

False Persistence

In early articles in the false memory literature, it was hypothesized that true memory responses would decline more slowly over time than false memory responses (for reviews, see Brainerd & Reyna, 2005; Gallo, 2006), for reasons that seemed obvious and intuitive at the time: Because the former involves remembering items that were actually presented and the latter involves remembering items that were not, true memory responses ought to be more resilient. However, the opposite effect, false persistence, follows transparently from the dual-recollection hypothesis.

Returning to the old/new condition of the standard false memory for occurrence design, suppose that the recognition test for half of the subjects occurs shortly after target presentations while the test for the other half is postponed for a week. Assume that all three retrieval processes exhibit forgetting over that interval. (It is unnecessary to assume anything about their relative forgetting rates or about the relative ability of targets and distractors to activate one process vs. another.) For targets, all the processes operate in

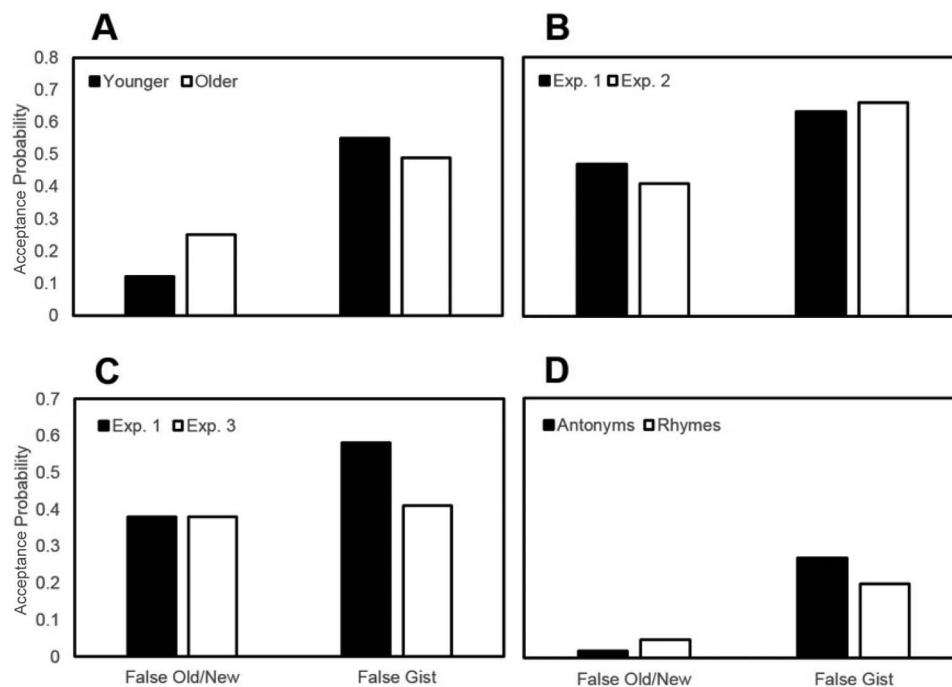


Figure 1. Examples of release from recollection rejection in experiments by Koutstaal (2003) on false memory for pictures from taxonomic categories (Panel A), by Brainerd and Reyna (1998) on false memory for semantic associates (Panel B), by Singer and Remillard (2008) on false memory for sentences (Panel C), and by Odegard and Lampinen (2005) on false memory for antonyms and rhymes (Panel D). Exp. = Experiment.

the same direction, supporting hits, so that a decline in any one of them will lower the hit rate. For related distractors, in contrast, the processes do not all operate in the same direction; context recollection and familiarity support false alarms, but target recollection supports correct rejections. Therefore, forgetting of these processes will have opposing effects on false alarms, with errors decreasing as a function of forgetting of context recollection or familiarity but increasing as a function of forgetting of target recollection. Two predictions follow, both of which are counterintuitive. The more obvious one is the false persistence effect, that as long as related distractors provoke target recollection a significant portion of the time on immediate tests, false alarm rates will decline more slowly than hit rates. The less obvious one is a sleeper effect, that if target recollection happens to predominate on immediate tests, so that false alarm rates are more under its control than under the control of context recollection or familiarity, false alarms could increase over a delay.

The false persistence effect has been widely investigated, and it has been detected in many studies (Brainerd & Reyna, 2005; Gallo, 2006). As was the case for release from recollection rejection, it has been reported for a broad range of target materials, from word lists to live events. As illustrations, the four panels of Figure 2 show data from articles by Lampinen, Copeland, and Neuschatz (2001) on forgetting of true and false memories of objects in rooms, by Payne et al. (1996) on forgetting of true and false memories of word lists, by Singer and Remillard (2008) on forgetting of true and false memories of the events in narratives, and by Howe et al. (2010) on forgetting of true and false memories of emotional versus neutral terms. In each panel, the bias-corrected acceptance rates for targets and related distractors on an immediate test are plotted on the left, and the corresponding bias-corrected acceptance rates for targets and related distractors on a delayed test

are plotted on the right. The predicted effects stand out. On the one hand, acceptance rates for targets drop perceptibly in all of the immediate–delayed comparisons—the average across panels being from .71 to .55. On the other hand, acceptance rates for related distractors do not show such a trend. Instead, acceptance rates drop in two comparisons, though less than for their corresponding targets; remain constant in one comparison; and increase in the remaining four comparisons. Overall, there is a moderate immediate–delayed increase from .42 to .52.

Summing up, the idea that target recollection supports hits but suppresses false alarms to related distractors means that the two will follow different forgetting trajectories and predicts a pair of counterintuitive results. Both have been confirmed in multiple experiments. In contrast, it is difficult to see how current univariate models of recollection could explain why false memory responses, for which context recollection and familiarity should both be weaker than they are for true memory responses, could be forgotten more slowly than true memory responses, let alone how false memory responses could increase as forgetting proceeds. Without the addition of ad hoc assumptions, the obvious prediction of such models is the intuitive one that false memory responses will decline more rapidly than true memory responses.

Negative Relations Between Target R Judgments and False Memories

The third effect is a prediction that the dual-recollection hypothesis makes about a corpus of R/K data that we assembled from the false memory literature, a prediction that follows from the same two ideas that have been used to explain why false memory can react in opposite ways to manipulations that increase true R judgments and to make other predictions. Suppose that R/K judg-

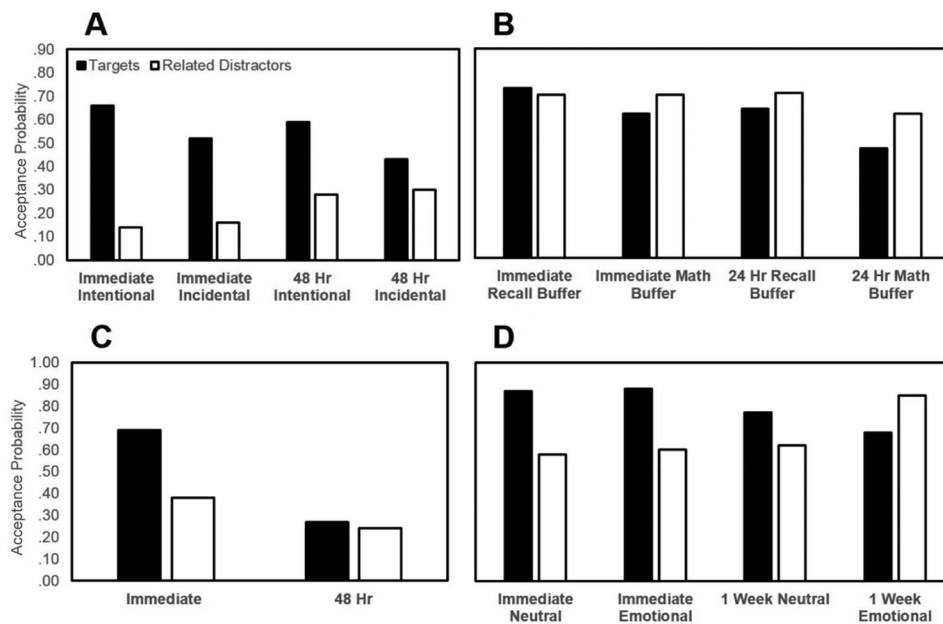


Figure 2. Examples of the false persistence effect as reported in articles by Lampinen, Copeland, and Neuschatz (2001; Panel A); Payne, Elie, Blackwell, and Neuschatz (1996; Panel B); Singer and Remillard (2008; Panel C); and Howe, Candel, Otgaar, Malone, and Wimmer (2010, Panel D).

ments are added to the old/new condition of the standard false memory for occurrence design, and experiments are conducted with manipulations that are known to increase true R judgments. Although hundreds of simple recognition experiments have incorporated R/K judgments, yielding stable patterns for manipulations such as those that were featured at the start of this article, a search of the literature identified fewer than 100 false memory articles that reported R/K data. We identified 77 articles with one or more conditions that yielded usable R/K data for targets and related distractors and extracted the results for those conditions. This yielded a total of 369 conditions in which R and K probabilities were reported for both types of probes and, in the preponderance of conditions, for unrelated distractors as well (see Appendix A for a description of this corpus). The corpus can be subdivided into (a) 266 conditions in which the Deese–Roediger–McDermott (DRM; Deese, 1959; Roediger & McDermott, 1995) illusion was the false memory task and (b) 103 conditions in which an assortment of other false memory tasks were used, such as false memory for unrepresented category exemplars, sentences, and pictures.

We used this corpus to test a prediction about the relation between true R judgments and false alarm rates for related distractors. If target R judgments tap two forms of recollection that both support hits, then such judgments are mixtures of target recollection, context recollection, and the usual familiarity and bias contaminants. In contrast, false alarms to related distractors only involve the last three processes because target recollection supports correct rejections. Across a range of experimental conditions that make recollective support differentially available/accessible on memory tests, the last three components of target R judgments will covary positively with false alarms, but the first will covary negatively. Thus, if the target R variance that is due to factors other than target recollection can somehow be reduced or removed, then across the conditions in this corpus, the target R probability ought to be a strong negative predictor of the false alarm probability (because target recollection suppresses false alarms).

That can be accomplished with a multiple regression analysis in which the target R probability is the predictor variable, the false alarm probability for related distractors is the criterion variable, and the target R probability's correlations with other variables to which context recollection, familiarity, and bias contribute are partialled out. Those other variables are the related and unrelated distractor R probabilities and the unrelated distractor false alarm probability. When the target R variance that is due to processes other than target recollection was reduced in this manner, we found that the target R probability was indeed a strong negative predictor of false alarms to related distractors. For the corpus as a whole, the resulting partial correlation between the target R probability and the false alarm probability for related distractors was $r = -.58$, $p < .0001$. For the subgroups of DRM conditions and conditions with other types of false memory tasks, the correlations were $r = -.53$, $p < .0001$, and $r = -.70$, $p < .0001$, respectively. These results, like release from recollection rejection and false persistence, are consistent with the dual-recollection hypothesis's proposal that target recollection suppresses false alarms.

Recollection Without Remembering

The fourth effect, which occurs in source memory experiments, is quite perplexing from the perspective of traditional formal models of source monitoring (Batchelder & Riefer, 1999), which rely on the univariate conception of recollection. It is predicted by the dual-recollection hypothesis, however, and it is the complement of the recall illustrations of target-recollection-without-context-recollection that we presented earlier. To recapitulate those illustrations, subjects exhibit no memory for contextual details that accompanied certain targets when the targets themselves are being recollected because they just read them out of consciousness on a recall test (Mickes et al., 2013; Shimamura & Squire, 1987). In the complementary source memory effect, subjects are able to recollect contextual details that accompanied the presentation of certain targets when they cannot remember the targets themselves.

Because source memory focuses on subjects' ability to retrieve details that were deliberately associated with target presentations, it is widely treated as tapping context recollection directly (e.g., Ingram et al. 2012; Yonelinas, 2002). In the typical experiment, targets are presented in two distinct contexts (e.g., List 1 vs. List 2, red print vs. blue print), followed by an old/new recognition test plus source judgments. The latter, like R/K judgments, are only requested after old decisions; that is, subjects are asked to report the presentation contexts of probes that are identified as old *but not of probes that are identified as new*. The theoretical rationale is that source memory is sufficient for identifying targets as old, so that dividing targets that are not identified as old into those for which contextual details can and cannot be recollected is nonsensical. This notion is implemented in formal models of source memory—in the form of an assumption that recollecting the context in which an unremembered target was presented is a zero-probability memory state (Batchelder & Riefer, 1999). With respect to the dual-recollection hypothesis, this assumption implies that context recollection guarantees target recollection.

As various authors (e.g., Ceci, Fitneva, & Williams, 2010; Cook, Marsh, & Hicks, 2006) have commented, the assumption that source memory is sufficient for identifying targets as old is never tested in the standard design, owing to the absence of source judgments following new decisions. That constraint has been removed in a few experiments, and the results have not been such as to confirm the assumption. In particular, reliable source memory has been observed for targets that were mistakenly identified as new. For instance, in two experiments with a task in which picture targets were presented in different spatial locations to children of two ages, Ceci et al. (2010) found that source memory was well above chance for pictures that were identified as new (39% overall; chance = 25%). In three experiments with adults that used more traditional word-list designs, Starns, Hicks, Brown, and Martin (2008) likewise found that source memory was above chance for targets that had been identified as new. Finally, Brainerd, Reyna, Holliday, and Nakamura (2012) reported some experiments in which recognition tests were accompanied by two types of source tests—yes–no judgments about correct source details (contexts in which target probes were presented) and incorrect source details (contexts in which target probes were not presented). Across experiments, the expected chance percentage of correct

source judgments for targets that were identified as new was 50%, but the observed percentage was 62%, a highly reliable difference.

To date, the theoretical significance that has usually been attached to source memory without target memory is that it supports the hypothesis that context recollection is continuous rather than discrete (Ceci et al., 2010; Kurilla & Westerman, 2010). If context recollection is continuous, it can be represented as a signal detection process in which source memory depends on whether the context recollection signal exceeds the decision criterion for that dimension (Starns et al., 2008). In such a model (cf. Starns et al., 2008), recognition and source judgments depend on separate recognition and source evidence signals, respectively. Occasionally, the source signal exceeds its criterion but the recognition signal does not, producing accurate source judgments without target recognition. Furthermore, the recognition and source evidence signals are positively correlated in this model, and hence, source memory without target recognition is more likely to happen when the recognition criterion is very conservative. Consistent with such reasoning, Starns et al. (2008) found that when subjects were given test instructions that should affect the recognition criterion (whether the test list contained 25% targets or 75% targets), the instructions did not affect the accuracy of old/new recognition, but the probability of correct source judgments for targets that were thought to be new was higher with conservative than with liberal instructions.

This model also predicts that the accuracy of old/new recognition and source judgments will be positively correlated over conditions and that, within a condition, source memory will be more accurate for targets that are recognized as old than for targets that are not. The reason, once again, is the positive correlation between the recognition and source evidence signals. Thus, over conditions and within conditions, as the strength of the recognition signal increases (making target recognition more likely), the strength of the source signal tends to increase, too (making target recollection more likely). Brainerd et al. (2012) failed to confirm either prediction in four experiments that supplied 40 conditions in which source memory with and without target recognition could be estimated. Across conditions, the correlation between the two was low and negative, and pooling over conditions, the probability of correct recognition given correct source memory was .36 while the probability of correct recognition given incorrect source memory was .38. According to the dual-recollection hypothesis, strong dependencies between source memory and target recognition are not expected if target recollection is the predominant mode of recollection with target probes; that is, if the recollective process associated with hits is overwhelmingly target recollection and the recollective process associated with source probes is retrieval of contextual details, correct source memory would not necessarily be strongly correlated with hits.

Further results in this vein that are congruent with the dual-recollection hypothesis have been obtained with recall. If episodic memory performance is a combination of context recollection and familiarity (but not target recollection), source memory without target memory should not occur when recollection is essential for accurate target memory, and over conditions in which source judgments and memory performance vary in accuracy, the correlation between the two should be strong. A natural way to test these predictions is to replace recognition tests with recall tests in source monitoring experiments. Recall has long been viewed as being based almost entirely on recollection (e.g., Mandler, 1980)—a key reason being that phenomenologically, subjects experience items as appearing in conscious awareness just before they read them out on a recall test. Also,

empirically, it will be remembered that in Tulving's (1985) original R/K article, subjects displayed very high levels of R judgment (88%) for words that they had just output on a free recall test. Hence, it ought to be especially difficult to detect source memory without target memory on recall tests, and source memory should be nearly perfect for recalled items. According to the dual-recollection hypothesis, however, if target recollection is the predominant recollective process in recall, as current dual process models of recall posit (Brainerd et al., 2009; Gomes, Brainerd, Nakamura, & Reyna, 2014), source memory without target memory should be clearly in evidence on recall tests, and recall need not be strongly correlated with source judgments.

In that connection, Cook et al. (2006) reported five experiments in which subjects studied cue–target word pairs presented in two contexts, followed by a distractor task, followed by associative recall tests. During the study phase, the cue member of each pair was first presented visually, followed by oral presentation of the target member in one of two contexts (e.g., male voice or female voice). During the test phase, a source judgment was requested for contextual details that had accompanied the presentation of the target *but not cue* member of each pair, regardless of whether the target member was recalled. Over the five experiments, there were a total of 16 conditions, and across those conditions, source judgments for unrecalled targets were correct 66% of the time (chance = 50%), which is slightly higher than in Starns et al.'s (2008) recognition experiments. Across the same conditions, source judgments for recalled targets were far from perfect and only slightly higher (71%). Similarly, Kurilla and Westerman (2010) reported two experiments in which subjects studied word lists presented in two contexts, followed by a fragment completion test. Regardless of whether the fragment produced correct recall, a source judgment was requested about the list on which the corresponding word had been presented. Across conditions and experiments, source judgments for targets that were not recalled were correct 66% of the time (chance = 50%), and furthermore, source accuracy was no better for targets that were recalled (63% overall).

In short, source memory for targets recognized as new has been found to be well above chance, which is consistent with the dual-recollection hypothesis but also with univariate signal detection models of recollection. However, the dual-recollection hypothesis also predicts that source memory need not be correlated with target recognition across conditions and that, within conditions, source recollection will not necessarily be more accurate for targets that are recognized as old. Furthermore, the dual-recollection hypothesis predicts that even when memory tests are altered to require strong reliance on recollection, the phenomenon of source memory without target memory will be preserved, and the lack of difference in source memory for remembered versus unremembered targets will persist.

Finally, there are some other experiments in which (a) subjects made source judgments following new as well as old recognition decisions but (b) source memory for targets recognized as new did not exceed chance (Slotnick & Dodson, 2005; Yonelinas, 1999). When we examined the methodologies of these experiments, we discovered that their source judgment procedures guaranteed this null result. Subjects rated their confidence in their memory for an item's source on a numerical scale that ranged from sure Source A to sure Source B, with a midpoint of no source memory. Source judgments for an item immediately followed the old/new recognition decision, and subjects were instructed that whenever they

decided that an item was new, they should assign it the midpoint of the source scale. Thus, the accuracy of source judgments following new decisions could not exceed chance unless the subjects failed to follow instructions.

Modeling Dual Recollection

So far, we have seen that a broad theoretical and empirical case can be made for a bivariate conception of recollection. Now, we formalize that notion in three types of dual-recollection models—a pure multinomial model, a mixed multinomial and signal detection model, and a pure signal detection model. This formalization allows the issue of whether the two varieties of recollection (and familiarity) ought to be represented as continuous or discrete variables to be treated as an empirical question when the models are applied to data. It also allows any overall conclusions that emerge to be less model dependent than is usual in this type of work. Before considering the models, however, a paradigm is required that factors all of the theoretical processes and yields an identifiable parameter space for those processes. Also, the question of whether target recollection should be modeled as a discrete or continuous process needs to be aired.

Conjoint Recognition

Earlier, we mentioned that the phenomenon of release from recollection rejection can be detected in false memory for occurrence designs by adding a second instructional condition to old/new recognition. That condition is one in which subjects accept related distractors as well as targets while continuing to reject unrelated distractors. By adding a third condition, the memory processes that have to be disentangled—target recollection, context recollection, and familiarity—can all be separated for related distractor probes because they produce unique response patterns over conditions. The third condition is one in which subjects accept only related distractors while rejecting targets as well as unrelated distractors. For simplicity, the conditions in which subjects are supposed to accept only targets, only related distractors, or both are denoted V, G, and VG, respectively. When they are factorially crossed with three types of test probes (targets, related distractors, and unrelated distractors), they form the conjoint recognition procedure (Brainerd et al., 2001).

The manner in which this procedure disentangles the three retrieval processes can be explained without reference to models or parameters, with the aid of Table 2. The accept–reject response patterns over the three conditions are shown at the top of Table 2 for related distractors and at the bottom for targets. In the second column, it can be seen that context recollection produces the same response outcome and, hence, the same cognitive state in each condition for both related distractors and targets. In the third column, it can be seen that familiarity likewise produces the same response outcome and the same cognitive state in each condition for both related distractors and targets. In the first column, however, it can be seen that target recollection produces different response outcomes and, hence, different cognitive states for related distractors versus for targets. When target recollection occurs, we assume that the retrieved content is compared to the test probe that generated it, yielding a perception of contrast for a related distractor but a perception of identity for a target. That leads to different

Table 2
Responses to Related Distractor and Target Probes That Are Supported by the Three Retrieval Processes in the Three Conjoint Recognition Conditions

Condition	Retrieval process		
	Target recollection	Context recollection	Familiarity
Probe = related distractor			
V: Accept targets	Contrast-reject	Accept	Accept
G: Accept related distractors	Contrast-accept	Reject	Accept
VG: Accept both	Contrast-accept	Accept	Accept
Probe = target			
V: Accept targets	Identity-accept	Accept	Accept
G: Accept related distractors	Identity-reject	Reject	Accept
VG: Accept both	Identity-accept	Accept	Accept

response outcomes for the V and G conditions. For related distractors, the overall response pattern for the three conditions is different for each of the three retrieval processes: Target recollection supports acceptance in the G and VG conditions but rejection in the V condition, context recollection supports acceptance in the V and VG conditions but rejection in the G condition, and familiarity supports acceptance in all three conditions. Hence, various types of models can be defined over the related distractor data of conjoint recognition that have the shared property that they deliver identifiable parameters for all of the processes.

For targets, on other hand, it can be seen at the bottom of Table 2 that although the response pattern over conditions is different for familiarity than for either variety of recollection, the patterns for target recollection and context recollection are the same (acceptance in the V and VG conditions but rejection in the G condition). Because target and context recollection thus cannot be factored with target data unless additional modeling constraints are imposed, we begin by modeling and measuring these processes with related distractor data in this section of the article and in the next section. Once it has been established that this can be done successfully, we return to the question of how to measure the two recollections with target data, and we introduce some testable constraints that allow all three retrieval processes to be measured simultaneously for both target and related distractor data (see the section Modeling Dual-Recollection Processes With Target Data).

The key advantages conferred by the fact that target recollection, context recollection, and familiarity can all be factored with the related distractor data of conjoint recognition are that rather than having to wait for experiments to accumulate in the literature, immediate progress can be made on measuring the two recollections and answering theoretical questions about them. That is because a corpus of data sets exists for this paradigm (see Appendix A)—so that once models containing identifiable parameters for all the retrieval processes are defined over it, such basic questions as the comparative fit of models that posit one versus two recollection processes, the nature of the statistical relations among the processes, and the manner in which individual parameters react to selected manipulations can all be studied.

Continuous and Discrete Recollection

As one surveys models of context recollection and familiarity retrospectively, back to Mandler's (1980) original high-threshold model, three stages can be discerned in the evolution of thinking on whether these processes ought to be modeled as discrete or continuous variables. At first, both were treated as discrete, with Jacoby's (1991) process-dissociation model being the most influential example of that stage. There are various ways in which memory processes can be modeled as discrete variables, of course, with finite Markov chains being well-known examples (cf. Greeno, 1974). In recognition research, high-threshold models, which can be conveniently represented as multinomial processing trees (Batchelder & Riefer, 1990), have predominated. During the second stage, models that were mixtures of high-threshold and signal detection assumptions became prevalent, following Yonelinas's (1994) initial formulation of such a model. He proposed that whereas recollection of contextual details should still be viewed as a discrete variable, familiarity varies through a range of strengths and, hence, ought to be modeled as a continuous variable. More recently, during the third stage, both processes have been viewed as continuous variables, leading to pure signal detection models of context recollection and familiarity, such as the sum-difference model (Rotello et al., 2004) and the continuous dual process model (Wixted & Mickes, 2010). In these latter models, the theoretical argument that justifies a continuous conception of context recollection runs as follows. There are many details that coincide with target presentations, details that vary along multiple dimensions (e.g., auditory vs. visual, physical vs. cognitive, criterial vs. noncriterial). From probe to probe, different numbers of such details, representing different mixtures of dimensions, can be retrieved. That, in turn, means that the degree of phenomenological realism that is conferred by consciously reinstated details will vary—graded recollection, in other words. Of course, the degree of phenomenological realism may vary as a function of the quality as well as the quantity of reinstated details; some details are more subjectively vivid than others (Gallo, 2013).

If such reasoning is accepted, we are left with the question of how target recollection ought to be modeled. There are plausible arguments on both the discrete and continuous sides. Intuitively, the natural way to think of target recollection is as a discrete process. If, instead, target recollection were graded, then from probe to probe, targets would be recollected as being (say) weakly, moderately, strongly, or definitely on the study list. That seems existentially nonsensical, rather like thinking of a person as being partly dead or partly human. Even if we acknowledge that the target items in memory studies are normally defined as collections of semantic, orthographic, and phonological features (e.g., Grondin, Lupker, & McRae, 2009) and allow for the possibility that different numbers and types of encoded features could be retrieved for different probes, it would seem that target recollection itself would have to be a threshold process—that there would be some proportion of retrieved features above which subjects would perceive that an item had been presented and below which they would not. Otherwise, target recollection would be a continuum of partial awareness of list membership, which does not square with the notion of clearly recollecting that an item occurred (Tulving, 1985).

Although the discrete view of target recollection seems intuitive for individual items, this process could nevertheless be expressed in a graded manner if rejection of related distractors depends on

how many targets are recollected. This possibility arises routinely in false memory research because the most common type of design is one in which related distractors share salient features with multiple targets—as when related distractors (*drums, trombone*) are unrepresented exemplars of a taxonomic category that was instantiated by multiple items on the study list (*piano, trumpet, guitar, clarinet, base*; e.g., Tussing & Greene, 1999). Gallo (2004) pointed out in connection with such tasks that correct rejections might increase as the number of presented exemplars that are recollected increases. In a design that combined false recognition with recall, he found that, indeed, unrepresented exemplars were more often rejected as target recall became more exhaustive. An analogous finding has been reported for the much-studied DRM illusion, which is another instance of a task in which related distractors overlap with multiple targets. Normative data on a large pool of DRM lists show that they vary in the mean number of targets that are output on free recall tests, from a low of 7.5 words to a high of 10.8 words (Roediger, Watson, McDermott, & Gallo, 2001). For these lists, the correct rejection probability for related distractors ranges from a low of .26, for lists for which eight or fewer targets are recalled, to a high of .56, for lists for which 10 or more targets are recalled. Similarly, in the misinformation paradigm, there is a strong correlation between how many of the original target items subjects can recall and their ability to reject distractors that were suggested during the misinformation phase (Belli, 1993).

In sum, theoretical analysis of target recollection does not provide unambiguous guidance as to whether it should be modeled as a discrete or a continuous variable. Neither does the type of data that has been used to adjudicate this same question for targets in simple recognition designs—namely, ROC curves. Such data are pertinent because the known properties of target ROC curves in the presence of a dominant discrete process (linearity in probability space, curvilinearity in z -normalized space; Yonelinas, 1999) also hold for related distractor ROC curves in which false alarms to related distractors are plotted against false alarms to unrelated distractors (Lampinen, Odegard, Blackshear, & Toglia, 2005). In addition, Rotello (2000) showed that if a discrete process sometimes produces rejections of related distractors, ROC curves in which target hit probabilities are plotted against related distractor false alarm probabilities will have a particular property: They will intersect the upper x -axis at a point $p(x) < 1$, with the quantity $1 - p(x)$ providing an estimate of how often the process operates.

ROC data on such predictions are mixed. For instance, Lampinen and associates have reported a series of experiments in which probability ROCs were plotted for related distractors, using tasks common in the false memory literature, such as the DRM illusion, schematic false memory, and conjunction lures (Lampinen & Arnal, 2009; Lampinen, Odegard, et al., 2005; Lampinen et al., 2004; Lampinen, Watkins, & Odegard, 2006). Overall, the linear ROCs that are predicted when a dominant discrete process is operating have sometimes been obtained (Lampinen et al., 2004), but related distractor ROCs have more often been curvilinear (Lampinen et al., 2006). Moreover, linear and curvilinear ROCs have sometimes been obtained in the same experiment for different types of related distractors (Lampinen, Odegard, et al., 2005). With respect to Rotello's (2000) reduced-intercept prediction about target versus related distractor ROCs, that prediction has been confirmed under several conditions, though it has failed under certain conditions, such as speeded testing and when subjects are not

explicitly instructed to use target recollection to reject related distractors (see Rotello, 2000). In addition, the false memory tasks that were used in those experiments were not typical ones for the false memory literature in that (a) each related distractor overlapped with only a single target and (b) each related distractor was physically very similar to its corresponding target (e.g., *computer* vs. *computers*). The first property may confine target recollection to recollection of individual targets, rather than groups of targets, which we saw earlier may favor discrete expression of this process.

A further complexity is that Bröder, Kellen, Schutz, and Rohrmeier (2013) have recently shown that the properties of ROCs that have been treated as diagnostic of whether recollection is continuous or discrete depend on other factors. In particular, Bröder et al. showed that (a) the properties that have been treated as diagnostic of discrete processes (linearity in probability space, curvilinearity in z -normalized space) depend on the confidence-mapping functions that are posited in threshold models and that (b) when mapping functions are introduced that are more realistic than those that have traditionally been used, threshold models and signal detection models both predict curvilinear ROCs in probability space and linear ROCs in z -normalized space.

Considering the mixed theoretical and empirical picture on the discrete versus continuous question, it seemed prudent to develop models that allow for either possibility and to compare them. Such a comparison is instructive because models that treat psychological processes as either discrete or continuous make different assumptions about the structure of the focal data (see Pazzaglia, Dube, & Rotello, 2013) and can provide different explanations for the effects of the same manipulation (e.g., Kinchla, 1994). Therefore, in the next subsection, we describe three models, each of which can be thought of as representing one of the historical stages in the evolution of recollection-familiarity models. The overall flow is that target recollection and context recollection are both modeled as discrete processes in the first model, target recollection is modeled as discrete and context recollection is modeled as continuous in the second (reflecting recent theoretical arguments about that process; Rotello et al., 2004; Wixted & Mickes, 2010), and target recollection and context recollection are both modeled as continuous in the third (reflecting the possibility that target recollection might also be expressed in a graded manner).

Dual-Recollection Models

In Figures 3, 4, and 5, we exhibit three models of target recollection, context recollection, and familiarity for the related and unrelated distractor data of conjoint recognition that implement varying assumptions as to which processes are discrete and which are continuous. The first is a pure multinomial (high-threshold) model, which appears in standard tree-diagrammatic form in Figure 3, with one tree for each instructional condition and probe type. It treats all of the retrieval processes and bias, too, as discrete variables and has retrieval parameters R_{TC} , R_C , and F , which are the probabilities of above-threshold target recollection, context recollection, and familiarity, respectively. The high-threshold bias parameters for the V, G, and VG conditions are b_V , b_G , and b_{VG} , respectively. The model's expressions for accepting related and unrelated distractors in each condition appear at the top of Table 3, where it can be seen that they follow the earlier definitions in Table 2; that is, familiarity supports acceptance of

related distractors in all conditions, context recollection supports acceptance in the V and VG conditions but rejection in the G condition, and target recollection supports acceptance in the G and VG conditions but rejection in the V condition.

As usual with such models, this one has a parameter ordering in which some processes trump others—specifically, R_C , F , and bias only affect acceptance probabilities when target recollection fails, F and bias only affect acceptance probabilities when both target and context recollection fail, and bias only affects acceptance probabilities when all of the retrieval processes fail.² This produces a statistical constraint: Parameters that are lower in the trumping sequence are estimated with fewer data than those that are higher in the sequence, yielding a reliability decrement that works against parameters that are lower in the sequence. Thus, other things being equal, F estimates will be less reliable than R_{TC} and R_C estimates, and R_C estimates will be less reliable than R_{TC} estimates. Moreover, F estimates can be unreliable when values of R_{TC} and/or R_C are high, and R_C estimates can be unreliable when values of R_{TC} are high. (The bias parameters are affected to a smaller extent by the trumping sequence because these parameters are operative for unrelated distractors, where trumping does not occur; see Table 3.)

As usual in models of this sort, we assume that all processes operate in parallel and are independent of each other. Note that there is no inherent contradiction between the independence and the trumping assumptions. Instead, the independence assumption pertains to the probabilities of the *operation* of the processes, whereas the trumping assumption pertains to the *combination rules* whereby the operation of the processes maps onto overt responses. Thus, the notion that the operation of each process is stochastically independent of the operation of the other processes is compatible with the notion that when generating a response, the processes affect performance according to a specific sequence.

Whereas the multinomial model treats target recollection, context recollection, and familiarity as discrete variables, other models can be constructed in which some variables are discrete and others are continuous. These are mixed multinomial/signal detection models, and Figure 4 depicts a mixed model in which target recollection is discrete and context recollection and familiarity are continuous. Its expressions for accepting related and unrelated

² The fact that context recollection and familiarity do not affect performance when target recollection is above threshold does *not* mean that they are below threshold whenever target recollection is above threshold. Similarly, the fact that familiarity does not affect performance when context recollection is above threshold does not mean that familiarity is below threshold whenever context recollection is above threshold. On the contrary, we assume that all three processes operate independently and in parallel on memory tests and, hence, can be above or below threshold regardless of the status of the other processes. The consistency of this independence assumption with our model can be seen by considering the respective multinomial expressions (see Table 3) for the probability of a false alarm or a correct rejection of a related distractor in the V condition: $p_V(\text{RD}) = (1 - R_{TC})R_C + (1 - R_{TC})(1 - R_C)F + (1 - R_{TC})(1 - R_C)(1 - F)b_V$ and $1 - p_V(\text{RD}) = R_{TC} + (1 - R_{TC})(1 - R_C)(1 - F)(1 - b_V)$. Notice that these expressions are actually simplifications of the following expressions: $p_V(\text{RD}) = [(1 - R_{TC})R_C][F + (1 - F)] + (1 - R_{TC})(1 - R_C)F + (1 - R_{TC})(1 - R_C)(1 - F)b_V$ and $1 - p_V(\text{RD}) = R_{TC}[R_C + (1 - R_C)][F + (1 - F)] + (1 - R_{TC})(1 - R_C)(1 - F)(1 - b_V)$, where the bolded terms vanish under algebraic manipulation. Likewise, the tree diagrams in Figure 3 are based on the simplified expressions, and as in the previous example, they could easily be expanded to include the missing terms.

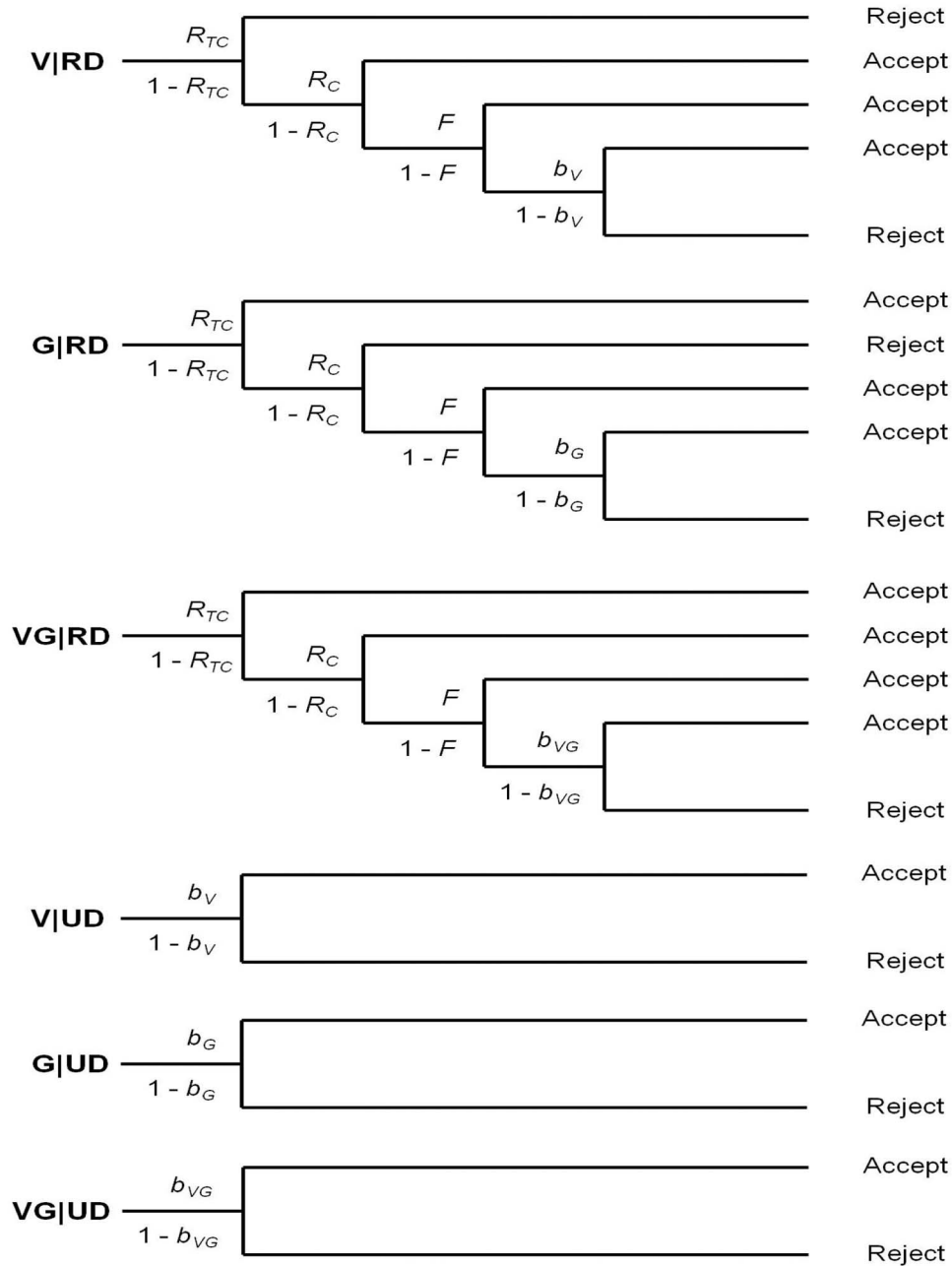


Figure 3. The multinomial dual-recollection model. V, G, and VG denote the *accept targets*, *accept related distractors*, and *accept both* conditions of conjoint recognition, whereas RD and UD denote related distractors and unrelated distractors, respectively. R_{TC} , R_C , and F are the probabilities that related distractors provoke above-threshold levels of target recollection-contrast, context recollection, and familiarity, respectively. b_V , b_G , and b_{VG} are bias parameters for the corresponding conjoint recognition conditions.

distractors in each instructional condition appear in the middle of Table 3. For the V and VG conditions, it is analogous to the sum-difference and continuous dual process models (Rotello et al., 2004; Wixted & Mickes, 2010), in which context recollection and familiarity are represented as continuous variables, except that there is an added discrete target recollection variable. Thus, this model captures current thinking that context recollection, as well

as familiarity, is a continuous process, and it also captures the intuition that target recollection is a discrete process. There are three panels in Figure 4, one for each instructional condition, with the discrete component of the model on the left and the signal detection component on the right.

Now, consider the possible memory events when a related distractor probe is presented. If target recollection succeeds in

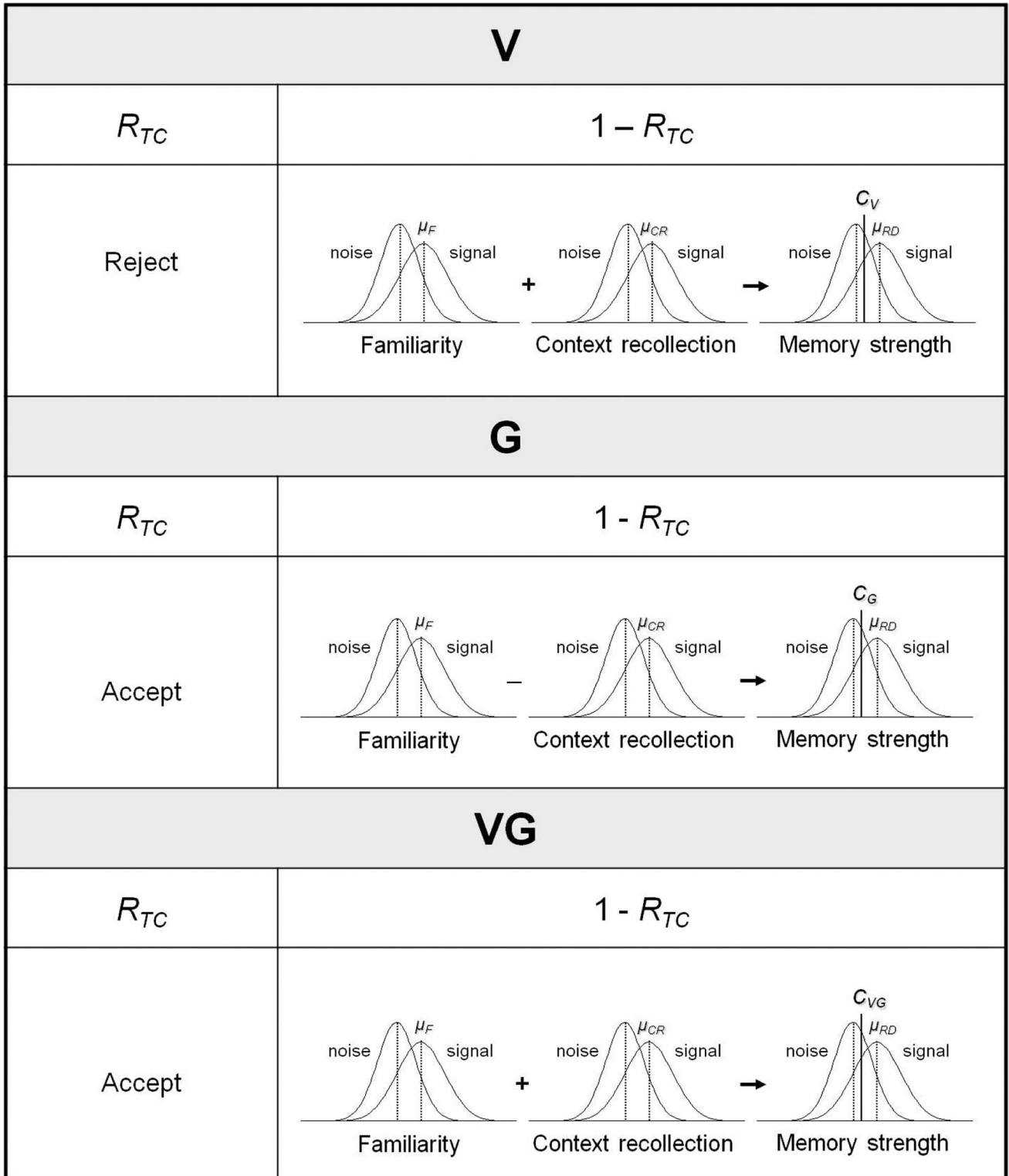


Figure 4. The mixed multinomial/signal detection dual-recollection model. V, G, and VG denote the *accept targets*, *accept related distractors*, and *accept both* conditions of conjoint recognition. R_{TC} is the probability that related distractors provoke above-threshold levels of target recollection-contrast. μ_F , μ_{CR} , and μ_{RD} are, respectively, the means of the signal distributions for familiarity, context recollection, and resulting memory strength for related distractors. C_V , C_G , and C_{VG} are decision criteria for the corresponding conjoint recognition conditions.

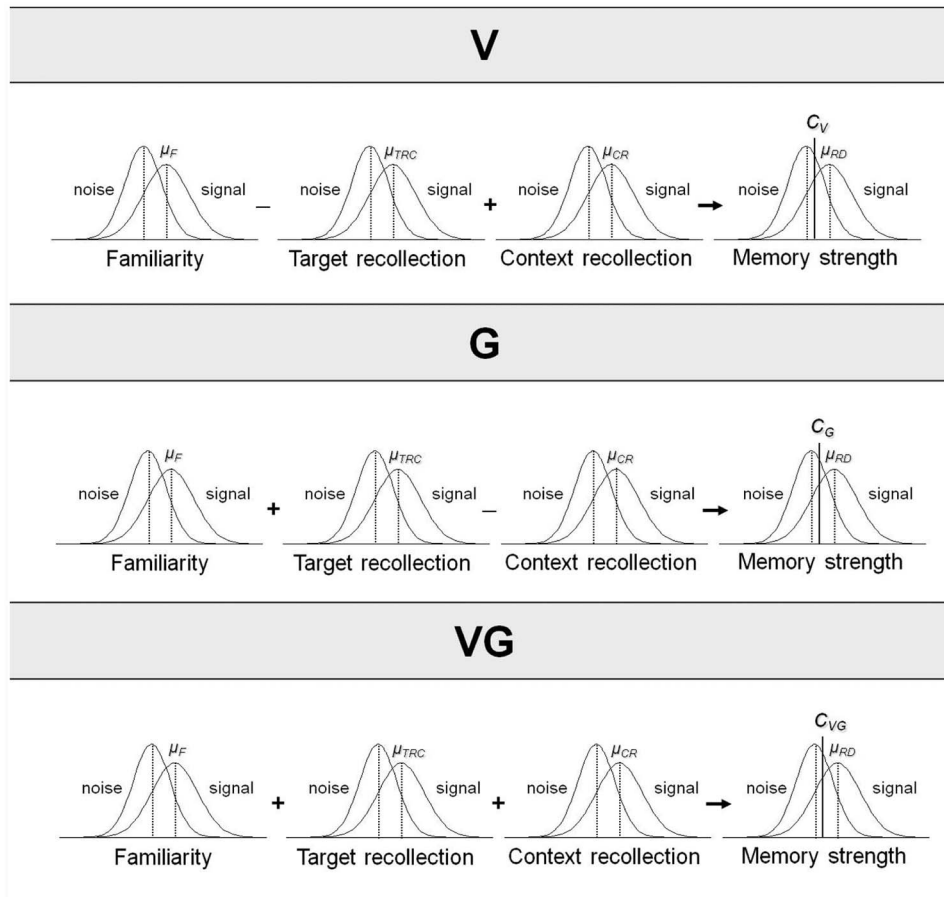


Figure 5. The signal detection dual-recollection model. V, G, and VG denote the *accept targets*, *accept related distractors*, and *accept both* conditions of conjoint recognition. μ_F , μ_{TRC} , μ_{CR} , and μ_{RD} are, respectively, the means of the signal distributions for familiarity, target recollection-contrast, context recollection, and resulting memory strength for related distractors. C_V , C_G , and C_{VG} are decision criteria for the corresponding conjoint recognition conditions.

producing the contrast state, the other component does not contribute to acceptance probabilities. If it fails, the other component operates as a standard bivariate signal detection model in the V and VG conditions (e.g., Macmillan & Creelman, 1991; Starns et al., 2008). In other words, there is a pair of Gaussian distributions for context recollection, a signal distribution (related distractors) and a noise distribution (unrelated distractors), a second pair of Gaussian distributions for familiarity, and a third pair for overall memory strength. When a probe is presented, a value is sampled from the appropriate context recollection distribution, a value is sampled from the appropriate familiarity distribution, and the values are added to produce a value of the signal or noise distribution for overall strength. To generate an accept-reject response, subjects set a decision criterion (C_V or C_{VG}), accepting probes whose overall strengths exceed the criterion. The signal detection component operates differently in the G condition. After context recollection and familiarity values are sampled, the overall strength value is generated by subtracting the former from the latter, and responses are then generated in the usual way by setting a decision criterion (C_G). Target recollection never occurs for unrelated dis-

tractors, and thus, these probes are always classified according to the signal detection component of the model.

This model has free retrieval parameters R_{TC} , μ_{CR} , and μ_F for related distractors, which are the probability of above-threshold target recollection, the mean of the signal distribution for context recollection, and the mean of the signal distribution for familiarity, respectively. There are also three free decision criterion parameters, of course (C_V , C_G , and C_{VG}). Owing to the multinomial component, there is a partial parameter ordering in which target recollection trumps context recollection and familiarity, so that μ_{CR} and μ_F only contribute to acceptance probabilities when target recollection fails. However, there is no parameter ordering in the signal detection component—within an instructional condition, μ_{CR} , μ_F , and the appropriate criterion parameter all contribute whenever target recollection fails. This allows for a possibility whose importance has been stressed in recent dual process models of recognition (see Wixted & Mickes, 2010): that some items can produce high levels of familiarity even though they produce low levels of reinstatement of contextual details. Statistically, the constraint of different parameters being estimated with different reli-

Table 3
Expressions for Acceptance of Related and Unrelated Distractor Probes in the Multinomial, Mixed, and Signal Detection Models in the Three Conjoint Recognition Conditions

Probe and condition	Expression
Multinomial model	
$p_V(\text{RD})$	$(1 - R_{TC})R_C + (1 - R_{TC})(1 - R_C)F + (1 - R_{TC})(1 - R_C)(1 - F)b_V$
$p_G(\text{RD})$	$R_{TC} + (1 - R_{TC})(1 - R_C)F + (1 - R_{TC})(1 - R_C)(1 - F)b_G$
$p_{VG}(\text{RD})$	$R_{TC} + (1 - R_{TC})R_C + (1 - R_{TC})(1 - R_C)F + (1 - R_{TC})(1 - R_C)(1 - F)b_{VG}$
$p_V(\text{UD})$	b_V
$p_G(\text{UD})$	b_G
$p_{VG}(\text{UD})$	b_{VG}
Mixed multinomial and signal detection model	
$p_V(\text{RD})$	$(1 - R_{TC})\Phi\left(\frac{\mu_{CR RD} + \mu_{F RD} - C_V}{\sqrt{\sigma_{CR RD}^2 + \sigma_{F RD}^2}}\right)$
$p_G(\text{RD})$	$R_{TC} + (1 - R_{TC})\Phi\left(\frac{\mu_{F RD} - \mu_{CR RD} - C_G}{\sqrt{\sigma_{CR RD}^2 + \sigma_{F RD}^2}}\right)$
$p_{VG}(\text{RD})$	$R_{TC} + (1 - R_{TC})\Phi\left(\frac{\mu_{CR RD} + \mu_{F RD} - C_{VG}}{\sqrt{\sigma_{CR RD}^2 + \sigma_{F RD}^2}}\right)$
$p_V(\text{UD})$	$\Phi\left(-\frac{C_V}{\sqrt{\sigma_{CR UD}^2 + \sigma_{F UD}^2}}\right)$
$p_G(\text{UD})$	$\Phi\left(-\frac{C_G}{\sqrt{\sigma_{CR UD}^2 + \sigma_{F UD}^2}}\right)$
$p_{VG}(\text{RD})$	$\Phi\left(-\frac{C_{VG}}{\sqrt{\sigma_{CR UD}^2 + \sigma_{F UD}^2}}\right)$
Signal detection model	
$p_V(\text{RD})$	$\Phi\left(\frac{\mu_{CR RD} - \mu_{TRC RD} + \mu_{F RD} - C_V}{\sqrt{\sigma_{TRC RD}^2 + \sigma_{CR RD}^2 + \sigma_{F RD}^2}}\right)$
$p_G(\text{RD})$	$\Phi\left(\frac{\mu_{TRC RD} - \mu_{CR RD} + \mu_{F RD} - C_G}{\sqrt{\sigma_{TRC RD}^2 + \sigma_{CR RD}^2 + \sigma_{F RD}^2}}\right)$
$p_{VG}(\text{RD})$	$\Phi\left(\frac{\mu_{TRC RD} + \mu_{CR RD} + \mu_{F RD} - C_{VG}}{\sqrt{\sigma_{TRC RD}^2 + \sigma_{CR RD}^2 + \sigma_{F RD}^2}}\right)$
$p_V(\text{UD})$	$\Phi\left(-\frac{C_V}{\sqrt{\sigma_{TRC UD}^2 + \sigma_{CR UD}^2 + \sigma_{F UD}^2}}\right)$
$p_G(\text{UD})$	$\Phi\left(-\frac{C_G}{\sqrt{\sigma_{TRC UD}^2 + \sigma_{CR UD}^2 + \sigma_{F UD}^2}}\right)$
$p_{VG}(\text{UD})$	$\Phi\left(-\frac{C_{VG}}{\sqrt{\sigma_{TRC UD}^2 + \sigma_{CR UD}^2 + \sigma_{F UD}^2}}\right)$

Note. $\Phi(\cdot)$ is the Gaussian cumulative distribution function. V = accept only targets; G = accept only related distractors; VG = accept both targets and related distractors; RD = related distractor; UD = unrelated distractor.

abilities is still present, but it is less severe than with the pure multinomial model. The target recollection parameter is still estimated with greater reliability than the other retrieval parameters because the latter only contribute when target recollection fails, but μ_{CR} and μ_F are estimated with comparable reliability because both contribute whenever the signal detection component operates.

Last, Figure 5 depicts the pure signal detection model, in which all three retrieval processes are continuous variables. This model captures current thinking that context recollection, as well as familiarity, is a continuous process, and it allows for the possibility that despite

our intuitions, target recollection might be expressed in a graded manner. The model's expressions for accepting related and unrelated distractors in each instructional condition appear at the bottom of Table 3. For the VG condition, it is a standard trivariate signal detection model. There are four pairs of Gaussian signal and noise distributions—one for target recollection (whose signal distribution is a contrast signal), one for context recollection, one for familiarity, and one for overall memory strength. Within each pair, the signal and the noise distributions correspond to related and unrelated distractors, respectively. When a probe is presented, values are sampled from the

appropriate target recollection, context recollection, and familiarity distributions and added to produce a value of the signal or noise distribution for overall strength. To generate responses, subjects set a decision criterion (C_{VG}), accepting probes that exceed the criterion. As in the signal detection component of the mixed model, this model operates differently in the G condition. After values have been sampled for target recollection, context recollection, and familiarity, the overall strength value is generated by summing the target recollection and familiarity values and subtracting the context recollection value. Responses are then generated in the usual way by setting a decision criterion (C_G) along the overall strength dimension. Similarly, for the V condition, after values have been sampled for target recollection, context recollection, and familiarity, the overall strength value is generated by summing the context recollection and familiarity values and subtracting the target recollection value from that sum. Responses are then generated in the usual way by setting a decision criterion (C_V) along the overall strength dimension.

This model has three free retrieval parameters μ_{TRC} , μ_{CR} , and μ_F , which are the means of the target recollection, context recollection, and familiarity distributions, respectively. There are also three free decision criterion parameters, as in the mixed model. Unlike either of the first two models, there is no ordering in which some parameters trump others. All three retrieval parameters contribute to acceptance probabilities on all related distractor probes, so that they are estimated with comparable reliability. Thus, a statistical limitation of the other two models is removed.

In applications of these three models to data, the methods that were used for estimating parameters and evaluating fit were similar to those that are widely used in the literatures on multinomial and signal detection models. The details of those methods have been relegated to [Appendix B](#).³

Afterword on Process Independence

As we saw, the multinomial, mixed, and signal detection models assume that target recollection, context recollection, and familiarity are stochastically independent. The implications of such assumptions for models of recollection and familiarity were comprehensively explored some years ago, with key conclusions being summarized in articles by Jacoby and associates (Jacoby, Begg, & Toth, 1997; Jacoby & ShROUT, 1997). One conclusion was that there is substantial evidence that recollection and familiarity are theoretically and empirically separable, that is, that they have distinct theoretical definitions and that various manipulations affect their behavioral measures differently. (With respect to target and context recollection, we have likewise shown that they are theoretically separable, and evidence of empirical separability is reported below.) A second conclusion was that whereas correlations between parameters that measure different processes are calculated across conditions, the process independence assumption in a model's equations pertains to stochastic independence within each of those conditions. Thus, the parameter correlations that are reported in the next section (e.g., in the factor analyses) are concerned with the issue of functional dependence of processes across conditions, which is fundamentally different than the issue of stochastic independence of parameters within conditions. Two processes can be stochastically independent within a condition yet be correlated across conditions (Jacoby & ShROUT, 1997).

Applications of Dual-Recollection Models

We investigated the multinomial, mixed, and signal detection models with a corpus of data sets that consists of the related and unrelated distractor data for all published and unpublished conjoint recognition experiments that we were able to locate. The experiments involved the types of materials and manipulations that are common in the false memory research (see [Appendix A](#)). There were 221 data sets. By applying all three models to each data set, we were able to resolve some basic questions about fit, about similarities and differences in the parameter values that the models generated, about the separability of target and context recollection, and about manipulations that selectively affect target versus context recollection. These questions are the foci of the four subsections that follow.

Model Fits

In this subsection, we report results that bear on three aspects of the ability of these models to account for the distractor data of conjoint recognition. The first and most important one is whether a bivariate conception of recollection is actually necessary to fit the data, or whether they are well fit by models that implement the traditional univariate conception. Second, if fit tests show that bivariate recollection is necessary, is it then possible to dispense with the familiarity process in models that posit bivariate recollection? Third, if fit tests show that target recollection, context recollection, and familiarity are all necessary, are they sufficient; that is, do models with just these three retrieval processes deliver satisfactory fits?

One recollection or two? We know that the dual-recollection hypothesis explains anomalous R/K data and predicts new findings, some of them counterintuitive. However, direct statistical tests of the assumption that distinct target and context recollection processes are needed to fit data would also be desirable. Despite the dual-recollection hypothesis's explanatory and predictive capabilities, models that contain only a context recollection process might deliver fits that are quite acceptable. We evaluated that possibility by fitting two versions of each of the three models to all of the data sets in the corpus.

As can be seen in [Table 3](#), the conjoint recognition data space (2 types of distractors \times 3 types of instructions) provides just enough free empirical probabilities to extract identifiable estimates of three retrieval parameters (target recollection, context recollection,

³ In the methods described in [Appendix B](#), the mixed and signal detection models assume that the combination of continuous retrieval processes into an overall memory strength signal uses unweighted sums and differences of signals from each process. However, other combination rules are possible. In particular, *weighted* sums have been used as a combination rule in some previous dual process models of recognition memory, such as the sum-difference theory of remembering and knowing (Rotello et al., 2004). For this reason, in addition to the unweighted versions of the mixed and signal detection models that are presented in [Appendix B](#), we developed alternative versions that used weighted sums and differences as the combination rule. When those versions were fit to the same data sets used to evaluate dual-recollection models later in this article (cf. the section Applications of Dual-Recollection Models), they yielded poor fits. Therefore, we only consider models using unweighted sums and differences as the combination rule. However, a full development of the weighted versions of the mixed and signal detection models is provided in the online supplemental materials, along with the results of goodness-of-fit tests.

familiarity) and three bias parameters (one for each instructional condition) for the multinomial model. For the mixed and signal detection models, we adopted two approaches to estimating the μ and C parameters (see Appendix B for details). The first used the unequal variance assumption that has become standard fare in simple recognition models: Memory and criterion parameters were estimated under the assumption that the variance of unrelated distractor (noise) distributions is smaller than the variance of target (signal) distributions. In our first series of analyses, we used that approach, assuming that related distractor distributions behave like target distributions with respect to having a greater variance (1) than unrelated distractor distributions (.8²). The mean of the former was a free parameter, and the mean of the latter was fixed at 0. The second approach used the equal variance assumption that was once common in recognition models, fixing the variance of related and unrelated distractor distributions at 1 but using the same assumptions about their means. We thought it advisable to repeat the analyses under that assumption because although there is extensive evidence in the literature that target distributions are more variable than unrelated distractor distributions, this issue has not been widely studied for related distractors. However, when the analyses were reprised under the equal variance assumption, the results were comparable. Consequently, we do not consider this matter further, and henceforth, all reported results have been generated under the unequal variance assumption.

If the target recollection parameter is eliminated (i.e., constrained to be zero) from the three models (R_{TC} in the multinomial and mixed models and μ_{TRC} in the signal detection model), each model is fit with one degree of freedom, yielding a $G^2(1)$ test of the null hypothesis that only a context recollection process is needed. This hypothesis was tested for each of the 221 data sets. The bottom-line result was the same for all of the models: The null hypothesis was rejected at high levels of confidence. The critical value for rejection is 3.84, and the mean values of $G^2(1)$ were 46.40 for the multinomial model and 21.95 for the mixed and signal detection models. (The latter are equivalent when their respective target recollection parameters are deleted.) The fit statistic had a positive skew in both instances, 1.99 for the multinomial model and 2.12 for the other models. Over the corpus, the G^2 statistic exceeded the critical value for 82% of the data sets with the multinomial model and for 72% of the data sets with the other models.

A consideration of the types of data sets for which fit failed suggests that these percentages are, if anything, underestimates of fit failure under the assumption of a single context recollection process. The corpus contains several data sets in which memory tests were administered after a delay of a few days to a week (see Appendix A), and as previously discussed, many R/K studies show that R judgments decline steeply across such intervals. Thus, if the dual-recollection hypothesis is correct in supposing that such judgments are mixtures of target and context recollection, the data of delayed tests are less sensitive measures of target recollection and, hence, would be expected to produce fewer rejections of models that posit a single recollection process. To evaluate this conjecture, we examined the data sets for which the G^2 statistic did not reject the corresponding model, and consistent with the hypothesis, roughly two thirds involved delayed testing.

For the sake of symmetry, we repeated these one-versus-two-recollections fit tests to evaluate the parallel assumption that target recollection was the only recollection process that was needed and

that the context recollection parameter could therefore be deleted from the models. When those models were fit to the data, the results were the same: Regardless of the model, the G^2 statistic rejected the null hypothesis of a single target recollection process for the great preponderance of data sets. The mean values of $G^2(1)$ were 20.63 (multinomial model), 24.96 (mixed model), and 24.42 (signal detection model). The fit statistic again had a positive skew in all three instances, 5.82 for the multinomial model, 5.83 for the mixed model, and 5.86 for the signal detection model. Over the corpus, the G^2 statistic exceeded the critical value for 66% of the data sets with the multinomial model, for 66% of the data sets with the mixed model, and for 61% of the data sets with the signal detection model.

Familiarity-free models. If models must include two recollection processes in order to fit the data, they are slightly more complex than current dual process models of target recognition (because they contain two recollection processes and a familiarity process, rather than one recollection process and a familiarity process). However, one can ask whether a familiarity process is still necessary when models contain both target and context recollection processes. Perhaps satisfactory fits can be now achieved with purely recollective models.

To evaluate that possibility, we conducted a third series of fit tests in which the familiarity parameter was eliminated, in turn, from the multinomial, mixed, and signal detection models and each model was refit to each data set in the corpus. Once again, the bottom-line result was the same for all three models: Overall, fits were not acceptable for any of the familiarity-free models. The mean values of the $G^2(1)$ statistic were 20.57 (multinomial model), 26.23 (mixed model), and 59.96 (signal detection model). As with the preceding fit tests for univariate recollection, the fit statistic had a positive skew in all three instances, 3.61 for the multinomial model, 3.51 for the mixed model, and 1.74 for the signal detection model. Over the corpus, the G^2 statistic exceeded the critical value for 66% of the data sets with the multinomial model, for 72% of the data sets with the mixed model, and for 87% of the data sets with the signal detection model.

Are target recollection, context recollection, and familiarity sufficient? So far, the fit tests have established that two recollection processes and a familiarity process are necessary to account for the data. Are they also sufficient, or do further processes need to be added to produce satisfactory fits? That is a question about the fit of the fully parameterized models to individual data sets in the corpus. As mentioned, however, the fully parameterized models are saturated (cf. Appendix B also), and thus, fit tests for individual data sets cannot be conducted. Parameter saturation is a routine characteristic of models of recollection and familiarity, the process-dissociation and sum-difference models being important cases in point. With such models, fit analyses are traditionally restricted to submodel comparisons like those that have been reported so far (i.e., tests of whether simplified versions of a model yield satisfactory fits).

Actually, however, it is possible to conduct fit tests for the fully parameterized versions of the present models by fitting them to pairs of data sets in the corpus, rather than to individual data sets. Specifically, if two treatment conditions of an experiment have little or no effect on false alarm rates for unrelated distractors, it is possible to test whether models with two recollection processes and a familiarity process are sufficient to account for the data of that pair of conditions. In such tests, the three retrieval parameters

are free to vary within conditions, but one, two, or three of the bias/criterion parameters are required to have the same value between conditions. This yields G^2 tests of fit with one, two, or three degrees of freedom, respectively.

When the corpus was examined, 12 experiments were identified in which the treatment conditions had little effect on the false alarm rates for unrelated distractors, particularly in the G and VG conditions. Therefore, for those experiments, the above fit methodology was implemented by constraining the bias/criterion parameters for the G and VG conditions to be equal across treatment conditions. The tests for each experiment were $G^2(2j)$ statistics, where j is the number of distinct pairs of treatment conditions that were compared in that experiment. The mean critical value to reject the null hypothesis of fit for the set of experiments as a whole was 7.34. The mean values of the fit statistic were 4.60 (multinomial model), 4.74 (mixed model), and 4.66 (signal detection model), with 83% of the individual values of the statistic failing to reject the null hypothesis of fit overall. In short, models with two recollection processes and a familiarity process were sufficient.

Intermodel Parameter Comparisons

To conduct intermodel parameter comparisons, we estimated the full set of parameters for each model for all of the conditions in the corpus. Mean parameter values for these models appear in Table 4. Regarding the mixed and signal detection models, their parameters were estimated in two ways—namely, with only the aforementioned constraints (on the variances of noise and signal distributions and on the means of noise distributions) and subject to the further constraint that estimates of the μ parameters had to be ≥ 0 . A comparison of the paired values for the two estimation methods revealed that they produced virtually no difference in mean parameter values, the average absolute difference between paired values of the μ parameters being .01. Consequently, this matter is not considered further, and the parameter values reported in Table 4 are those for the second method of estimation.

Next, we consider commonalities and differences among the models' parameter estimates. With respect to commonalities, there are three principal ones. The first and most fundamental one is an extension of some results that were recently reported by Batchelder and Alexander (2013) and concerns correlations among the models' respective estimates of the retrieval and bias/criterion parameters. Using

simulated data, Batchelder and Alexander found that correlations between multinomial and signal detection models' parameter estimates for simple recognition models were very high, ranging between .92 and .98. Similarly, for actual data from conjoint recognition experiments, the average correlation between the multinomial model's estimates of each of its parameters and the corresponding estimates of the mixed and signal detection models were .96 and .93, respectively, and the average correlation between the mixed and signal detection models' estimates was .98. Thus, Batchelder and Alexander's conclusion that multinomial and signal detection models "can generate very similar data patterns" (Batchelder & Alexander, 2013, p. 1208) also holds for conjoint recognition.

The second commonality concerns the bias/criterion parameters. Their ordering for each model tells the same story about how recognition instructions affect response bias. Whenever the instructions allow related distractors to be accepted, regardless of whether they also allow targets to be accepted, bias to accept increases. Thus, in the multinomial model, b_V is smaller than b_G or b_{VG} , whereas in the mixed and signal detection models, the decision criterion is more liberal when related distractors can be accepted (C_G and C_{VG}) than when they cannot (C_V). The third commonality concerns the absolute value of the target recollection parameter. The fit tests indicated that target recollection contributes significantly to performance because fits were poor when this process was deleted from the models. Consistent with that, note that the mean estimate of the target recollection parameter is well above zero in each model. In the multinomial and mixed models, in which this parameter is a probability, the tabled means indicate that roughly 20% of the responses to related distractors were based on target recollection.

Turning to differences among the models' parameter estimates, there is only one notable difference, which concerns estimates of the familiarity parameter, relative to estimates of the target and context recollection parameters. With the multinomial model, the mean estimate of F is comparable to the mean estimates of R_{TC} and R_C , suggesting that the tendencies of related distractors to provoke target, context recollection, and familiarity are approximately equal. With the mixed model, however, the suggestion is that related distractors provoke higher levels of familiarity than context recollection because the mean estimate of μ_F is more than 50% larger than the mean estimate of μ_{CR} . (Remember that in the mixed model, the target recollection parameter is not on the same measurement scale as the other parameters.) Furthermore, the suggestion with the signal detection model is that related distractors provoke higher levels of familiarity than either form of recollection because the mean estimate of μ_F is more than twice the mean estimates of μ_{TRC} and μ_{CR} . These different patterns may not represent substantive differences between the models and instead may merely reflect statistical bias in the estimation of F in the multinomial model, as follows.

We saw that a mathematical consequence of the parameter-ordering property of the multinomial model is that its familiarity parameter is estimated for smaller amounts of data than its recollection parameters—specifically, only for items for which both forms of recollection are below threshold. That can cause bias in the estimation of F if this parameter is not stochastically independent of the R_{TC} and R_C parameters at the Subject \times Item level (see Cowan & Stadler, 1996; Dodson & Johnson, 1996; Merikle, Joordens, & Stolz, 1995). The bias is downward if parameter dependency is positive and upward if it is negative (Brainerd et al.,

Table 4
Mean Values of the Three Models' Parameters for the Corpus of Conjoint Recognition Data

Parameters	Model		
	Multinomial	Mixed	Signal detection
Retrieval			
Target recollection	$R_{TC} = .23$	$R_{TC} = .19$	$\mu_{TRC} = .24$
Context recollection	$R_C = .17$	$\mu_{CR} = .25$	$\mu_{CR} = .20$
Familiarity	$F = .22$	$\mu_F = .40$	$\mu_F = .45$
Bias/criterion			
V condition	$b_V = .18$	$C_V = .81$	$C_V = .80$
G condition	$b_G = .30$	$C_G = .44$	$C_G = .44$
VG condition	$b_{VG} = .29$	$C_{VG} = .48$	$C_{VG} = .48$

Note. V = accept only targets; G = accept only related distractors; VG = accept both targets and related distractors.

2001). Thus, the lower estimates of F in the present multinomial model might be artifacts of positive Subject \times Item correlations between the F parameter and the R_{TC} and/or R_C parameters. This explanation cannot be directly tested, however, because, as noted earlier, parameter correlations cannot be computed at the Subject \times Item level.

This potential bias is not present to the same degree in the mixed and the signal detection models. Bias could still occur in μ_F estimates of the mixed model if this parameter were positively correlated with R_{TC} , but there is little indication of that because the mean value of μ_F rises by only .05 as we move from the mixed to the signal detection model. Thus, if the lower estimates of F for the present multinomial model are artifacts of lack of stochastic independence among parameters, positive F - R_C dependency is a more likely cause than positive F - R_{TC} dependency.

Factor Structure of Dual-Recollection Models

Statistical relations among estimates of the memory and bias parameters over the 221 data sets can be determined by factor analyzing each model's parameter space, which bears on the question of how functionally distinct target recollection and context recollection are across variations in experimental conditions. They are theoretically distinct, as we have seen, but over conditions, they might react quite similarly. If so, factor analyses of the models' parameter spaces will show that they load on common factors. To the extent that target recollection and context recollection are functionally independent processes, however, they will not react in the same manner over conditions and, hence, not load on common factors. We were also interested in the secondary question of whether increasing the incidence of target recollection makes decision criteria more conservative.

With respect to the question of primary interest, the dual-recollection hypothesis treats target and context recollection as distinct processes, and up to this point, theoretical considerations and empirical evidence have been congruent with that view. Obviously, this notion would be strengthened if, over a corpus of data sets that encompasses variations in manipulations, materials, and subject samples, target and context recollection occupied different regions of the factor space. With respect to the secondary question, it seems to us that beyond affirmative rejection of related distractors, target recollection ought to encourage generally more conservative decision criteria. Estimates of criterion placement (or bias in the multinomial model) are chiefly determined by the unrelated distractor data. Such items cannot provoke awareness of their prior presentations because they were not presented, and their familiarity levels are low because they do not share salient properties of targets. It seems reasonable, metacognitively, that across variations in conditions that make target recollection more common, subjects would be increasingly less likely to accept probes that neither cue recollective support nor seem familiar.

To answer such questions, we conducted principal components analyses of the 221 sets of parameter estimates, with orthogonal rotation of factors. For each model, two factors were extracted, using the conventional eigenvalue cutoff of 1. For Factor 1, the percentages of variance accounted for were 44% (multinomial model), 46% (mixed model), and 49% (signal detection model). For Factor 2, the percentages of variance accounted for were 23% (multinomial model), 20% (mixed model), and 20% (signal detection model). The

rotated loadings of the retrieval and bias/criterion parameters are shown for each model in Table 5. Loadings are blocked by parameter type (retrieval vs. bias/criterion parameters). Following the usual convention in which factor loadings $\geq .40$ are treated as significant, loadings that met that criterion are reported in Table 5.

Inspection of the factor loadings reveals that each factor has a simple process interpretation, which is the same for each model. Factor 1 is a target recollection/bias factor. Across models, the average loading of the three bias/criterion parameters was .86, and the target recollection parameter always loaded on this factor. Another important conclusion about bias/criterion placement that follows from the Factor 1 results is that this process behaves similarly in the three instructional conditions. It might be thought that bias/criterion placement would behave differently under instructions to accept unrepresented items (G and VG) than under the traditional instruction to accept only presented items (V). However, the factor loadings show that conditions that make criterion placement more conservative (or that lower bias) under V instructions do likewise under G and VG instructions.

Factor 2 is a context recollection/familiarity factor. Across models, the average loading of the context recollection parameter on this factor was .88. In addition, the familiarity parameter always loaded on Factor 2, so that conditions that increased the frequency of context recollection also made probes seem more familiar. Note the consistency between this pattern and the finding that false memory items whose content is highly familiar because it has been instantiated by multiple targets are especially likely to retrieve ersatz recollective support (e.g., Brainerd et al., 2001; Lampinen, Meier, et al., 2005).

Returning to the question of central interest, whether target and context recollection should be regarded as distinct processes, the parameter loadings supply additional evidence that they are indeed distinct. Over the three models, target recollection *never* loaded with context recollection; it always loaded with bias/criterion placement, while context recollection always loaded with familiarity. Note the consistency between this pattern and the recollection-without-remembering effect that we discussed earlier. If, over conditions, the ability to clearly remember that the presentation of specific targets is unrelated to the ability to retrieve contextual details that accompanied those presentations, it is quite reasonable that subjects would be able to retrieve contextual details for targets that cannot be recalled or recognized.

With respect to the question of secondary interest, the way in which the target recollection and bias/criterion parameters loaded on Factor 1 answers this question. Remember that the target recollection and bias/criterion parameters always loaded together on this factor and never on the other factor. With the multinomial model, the bias parameters loaded positively, and the target recollection parameter loaded negatively. With each of the other models, the criterion placement parameters loaded positively, and the target recollection parameter also loaded positively. Regardless of model, then, bias to accept unrelated distractors decreased as target recollection increased.

The conclusion that bias to accept unrelated distractors decreased as the overall level of target recollection increased leads to a further prediction that can be evaluated with two corpora of R/K data, the first of which was mentioned earlier in connection with predicted negative relations between target R judgments and false memory. This first corpus consisted of 369 data sets in which

Table 5
Loadings of the Parameters of Each Dual-Recollection Model on the Two Factors That Were Identified by the Factor Analyses

Parameter	Factors	
	Factor 1 (Target recollection/bias)	Factor 2 (Context recollection/familiarity)
Multinomial model		
Retrieval		
R_{TC}	-.69	
R_C		.84
F		.77
Bias		
b_V	.85	
b_G	.83	
b_{VG}	.86	
Mixed model		
Retrieval		
R_{TC}	.56	
μ_{CR}		.87
μ_F		.71
Criterion		
C_V	.83	
C_G	.89	
C_{VG}	.87	
Signal detection model		
Retrieval		
μ_{TRC}	.56	
μ_{CR}		.92
μ_F	.51	.62
Criterion		
C_V	.83	
C_G	.89	
C_{VG}	.87	

Note. The factor analyses of the parameter spaces of the multinomial, mixed, and signal detection models accounted for 67%, 66%, and 69% of the variance, respectively.

subjects made R/K judgments following old/new decisions about targets, related distractors, and unrelated distractors in false memory for occurrence experiments. The second corpus, which is more fully described in Appendix A, consists of 600 data sets in which subjects made R/K judgments following old/new decisions about targets and unrelated distractors in simple recognition experiments. According to findings that we have just reported, increases in target recollection are associated with more conservative decision criteria, whereas context recollection is uncorrelated with decision criteria. Because target R judgments are mixed measures of target and context recollection, both forms of recollection will increase monotonically across the range of conditions that increase the frequency of such judgments in each corpus. Because the decision criterion for any arbitrary condition i is a monotonic function of the false alarm probability for unrelated distractors [$FA_i = \Phi(-C_i/SD_i)$], the straightforward prediction is that over conditions, this false alarm probability will be negatively correlated with the target R probability. (This is because bias to accept unrelated distractors decreases as target recollection increases, but it is uncorrelated with increases in either context recollection or familiarity.) To test that prediction, we computed the partial correlation between target R judgments and unrelated distractor false alarms for the data sets

in both corpora. That correlation was highly reliable for both the simple recognition data ($r = -.50, p < .0001$) and the false memory data ($r = -.32, p < .0001$).

Summing up the findings in this section, although our three models differ in their assumptions as to whether and to what degree the three retrieval processes are discrete versus continuous variables, the factor structures of their parameter spaces were very similar. There was a target recollection/bias factor and a context recollection/familiarity factor. Target recollection and context recollection parameters never loaded on a common factor, providing further support for distinguishing two varieties of recollection. Also, target recollection was identified as a potential control process for criterion placement.

Effects of Manipulations on Retrieval Parameters

We now consider how the models' parameters reacted to specific manipulations in order to generate supplementary evidence on the separability of dual-recollection processes. We summarize results from four false memory experiments that involved two of the manipulations that are known to drive true R judgments up and false memory down (pictures vs. words, repetition) and two that are known to drive them in the same direction (full vs. divided attention, deep vs. shallow encoding). Here, the R/K literature, together with the dual-recollection hypothesis, supplies the primary theoretical justification for the parametric effects that are predicted: The dual-recollection hypothesis explains why manipulations that increase R judgments can drive false memory in opposite directions (because sometimes they increase target recollection relative to context recollection, and sometimes they do the opposite), and if that explanation is correct, these manipulations' predicted effects fall out.

We previously considered several examples of manipulations that increase the probability of R judgments for targets, some that have the further effect of decreasing false memory and others that have the surprising effect of increasing it. Among them were (a) presenting lists as pictures rather than as words and presenting lists multiples times rather than once, both of which decrease false memory, and (b) studying lists under full rather than divided attention and studying lists under deep rather than shallow encoding instructions, both of which increase false memory. According to the dual-recollection hypothesis, to the extent that differences in R judgments for these manipulations represent differences in recollective experience, the first two manipulations should drive target recollection up more than context recollection, whereas the last two should do the opposite. It is also possible to supply process reasons for why each manipulation that we studied should have the predicted effects. Concerning the first two, pictorial presentation and repetition have often been discussed in the false memory literature as manipulations that enhance memory for the exact surface structure of individual targets (Brainerd & Reyna, 2005), which ought to selectively increase target recollection. Concerning full versus divided attention, targets themselves are naturally more salient than contextual details, so that dividing attention ought to especially degrade processing of the latter (reducing context recollection). Likewise, concerning deep versus shallow encoding, the latter should degrade processing of contextual details because it focuses encoding on the surface structure of individual targets. Because these predictions center on target versus context recollection, they do not preclude familiarity effects for any of the manip-

ulations, and considering that R judgments are widely thought to be contaminated by strong familiarity (e.g., Heathcote et al., 2010; Malmberg, 2008), familiarity effects would not be remarkable.

Brainerd and Reyna (2003) described four very similar DRM experiments, each of which included one of the above manipulations, in a conjoint recognition design. In each experiment, subjects studied 16 of the DRM lists in the Roediger et al. (2001) norms and responded to recognition tests containing a total of 48 targets (three per DRM list), 16 semantically related distractors (the critical distractor for each of the lists), and 32 unrelated distractors. The picture-word, divided attention, and deep-shallow manipulations were between subjects, while the repetition manipulation was within subjects. The picture-word manipulation followed a methodology described in Schacter et al. (1999), the repetition manipulation followed a methodology described in Brainerd, Payne, et al. (2003), the divided attention manipulation followed a methodology described in Gruppuso, Lindsay, and Kelley (1997), and the deep-shallow manipulation followed a methodology described in Toglia et al. (1999). In the Schacter et al. procedure, study and test lists were presented as pictures with accompanying audio pronunciation of items or as printed words with accompanying audio pronunciation. In the Brainerd et al. procedure, lists were presented once or thrice as printed words. In the Gruppuso et al. procedure, printed word lists were presented alone (full attention) or accompanied by an auditory digit stream in which occurrences of 2 and 3 had to be reported (divided attention). In the Toglia et al. procedure, lists were presented orally, with subjects in the deep encoding condition rating each word on a 5-point pleasantness scale and subjects in the shallow encoding condition making yes-no decisions about whether each word contained the letter *a*. The overall procedure for each experiment consisted of two parts. During the first, eight DRM lists were presented (2.5-s rate), followed by a 5-min buffer activity (arithmetic problems), followed by a recognition test (24 targets, eight critical distractors, 16 unrelated distractors). During the second part, this procedure was repeated for the remaining eight lists. The subjects in each experiment were undergraduates, who participated for course credit, with 25 subjects per conjoint recognition condition in the repetition experiment and 30 subjects per condition in the other three experiments.

Our interest was merely to use these data to estimate model parameters and thereby test the predictions that the picture-word and repetition manipulations would affect target recollection more than context recollection and that the full-divided and deep-shallow manipulations would have the opposite effect. We estimated the parameters of all three models, and the results appear in Table 6. Throughout this section, whenever the effects of any manipulation on any parameter are reported as reliable, those effects were statistically reliable by the usual G^2 parameter invariance tests (e.g., Batchelder & Riefer, 1999). In such tests, for any parameter of any of the models, the likelihood of the data of a given condition is calculated under the constraint that the parameter has the same value for different levels of the manipulation, with the null hypothesis of equivalence being rejected when the G^2 statistic exceeds its .05 critical value.

With respect to the picture-word and repetition manipulations, it can be seen in Table 6 that both produced large, reliable increases in the target recollection parameter of each model but had negligible effects on the context recollection parameter. In addition, pictures produced a reliable increase in the familiarity parameter of the signal detection model, but not in the familiarity parameters of

Table 6
Estimates of the Dual-Recollection Models' Retrieval Parameters for Experiments 1–4

Experiment/condition	Retrieval parameters		
	TRC	CR	F
Multinomial model			
Experiment 1			
Pictures	.53	.17	.27
Words	.20	.19	.26
Experiment 2			
3 presentations	.45	.21	.26
1 presentation	.16	.21	.36
Experiment 3			
Full attention	.22	.49	.32
Divided attention	.19	.24	.22
Experiment 4			
Deep processing	.19	.09	.80
Shallow processing	.19	.12	.29
Mixed model			
Experiment 1			
Pictures	.48	.21	.62
Words	.16	.23	.46
Experiment 2			
3 presentations	.41	.26	.61
1 presentation	.11	.26	.60
Experiment 3			
Full attention	.19	.66	.54
Divided attention	.15	.28	.34
Experiment 4			
Deep processing	.15	.14	1.31
Shallow processing	.18	.16	.41
Signal detection model			
Experiment 1			
Pictures	.56	.14	.69
Words	.18	.19	.48
Experiment 2			
3 presentations	.51	.20	.61
1 presentation	.13	.24	.60
Experiment 3			
Full attention	.26	.56	.54
Divided attention	.17	.25	.35
Experiment 4			
Deep processing	.24	.13	1.17
Shallow processing	.22	.14	.40

Note. TRC, CR, and F are the target recollection-contrast, context recollection, and familiarity parameters, respectively, of the three models. Reliable differences are shown in bold type.

the other two models. Thus, the only effect of the picture-word and repetition manipulations that was detected by all of the models was an increase in target recollection. Turning to the divided attention manipulation, the results for the recollection parameters were as expected for all three models: There was a large, reliable increase in their context recollection parameters under full attention, but variations in their target recollection parameters were negligible. In addition, full attention produced a reliable increase in the familiarity parameter of one of the models (mixed), but not for the other two.

Finally, deep-shallow encoding did not yield the anticipated pattern and, instead, was found to be a pure familiarity manipulation by all three models. The manipulation did not affect either of the recollection parameters in any of the models but had large effects on of their

familiarity parameters. Except for the deep-shallow findings, then, the modeling results are in line with what the dual-recollection hypothesis expects on the basis of prior R/K studies and prior false memory studies of each of these manipulations.

Summary of Model Applications

In this section, we have examined some core questions about the dual-recollection models by applying them in four different ways to conjoint recognition data sets: (a) by conducting fit tests, (b) by comparing their respective estimates of the memory and bias/criterion parameters, (c) by factor analyzing their parameter spaces, and (d) by using their parameter estimates to identify process loci of the effects of specific manipulations. The major conclusions are these.

First, the fit analyses converged on the conclusion that target recollection and context recollection are both involved in recognition decisions about related distractors. When parameters for either recollection process were removed from the models, the null hypothesis of fit was rejected at high levels of confidence; both processes were always necessary to account for the data. The null hypothesis of fit was also rejected when familiarity parameters were removed from the models. Second, the intermodel comparisons of parameter estimates identified key commonalities among the models' respective estimates. The most important one was that, over the conditions in the conjoint recognition corpus, the models produced similar parametric results because their respective estimates of individual retrieval and bias parameters were highly correlated (range = .93–.98).

Third, the factor analyses provided strong support for the functional independence of target and context recollection over a broad range of conditions. All of the models produced the same two-factor solution, wherein target and context recollection parameters always loaded on different factors. Fourth, in that same vein, application of the models to specific experimental manipulations produced further support for the separability of target and context recollection. Based on earlier R/K studies and false memory studies, some manipulations were expected to increase target recollection more than context recollection, and others were expected to increase context recollection more than target recollection.

Modeling Dual-Recollection Processes With Target Data

In the preceding section, to gain leverage on bivariate recollection, we exploited the fact that the two recollections and familiarity can be jointly factored with the distractor data of conjoint recognition. For the paradigm's target data, however, we saw that unless additional constraints are imposed, none of the three models yields separate identifiable parameters for target and context recollection. Obviously, it would be desirable if the two recollections could be measured for target data as well as distractor data. Therefore, we conducted further analyses in order to determine whether there was any constraint that could be imposed on these models that would deliver an identifiable set of retrieval parameters for targets as well as distractors. It turned out that there was one that accomplished this for all three models.

That constraint is to assume that context recollection contributes to target and related distractor performance primarily in the VG condition, rather than the V and G conditions. The motivation

behind this idea is the fact (cf. Table 2) that although context recollection distinguishes targets and related distractors from unrelated distractors, it confuses related distractors with targets. This means that it produces errors for related distractors in the V and G conditions, where subjects know that such probes must be distinguished from targets, but it produces correct responses in the VG condition, where subjects know that they only have to distinguish unrelated distractors from related distractors and targets. Thus, it seemed plausible that, in order to minimize errors, it is mainly in the VG condition that subjects rely on context recollection. It should be stressed that context recollection continues to operate in the V and G conditions—our assumption merely being that subjects do not rely on it as a basis for their decisions because it hinders the main objective, which is to discriminate targets from related distractors. When that constraint is imposed, the multinomial, mixed, and signal detection models all yield identifiable parameters for target recollection, context recollection, and familiarity for both targets and related distractors, as well as identifiable bias/criterion parameters for each condition.⁴ However, to accommodate the fact that the cognitive state that is generated by target recollection is identity for target probes but contrast for related distractor probes, there are distinct target recollection parameters for the two types of probes. The parameters for targets are R_{TI} (multinomial and mixed models) and μ_{TI} (signal detection model), and the corresponding parameters for related distractors are R_{TC} and μ_{TC} .

We evaluated the acceptability of the aforementioned constraint as follows. Because the constrained models are saturated (each estimates nine parameters from the nine empirical probabilities of the conjoint recognition paradigm), acceptability cannot be evaluated by computing G^2 tests of models with more versus fewer

⁴ Mathematically, the constrained versions of the multinomial, mixed, and signal detection models for related distractors are simple revisions of the unconstrained versions that are presented in Appendix B and Table 3. The constrained multinomial model includes the R_{CR} parameter for related distractors only in the expression for $p_{VG}(\text{RD})$ because, although context recollection operates in all three conditions, VG is the only condition in which it affects subjects' responses. The constrained mixed and signal detection models both assume that the μ_{CR} and σ_{CR} parameters for related distractors are only present in the expression for $p_{VG}(\text{RD})$. The target parts of these models are straightforward extensions of the equations for related distractors. Specifically, a target recollection parameter, a context recollection parameter, and a familiarity parameter are also posited for target data, and it is assumed the context recollection parameter of each model is only present in that model's expression for $p_{VG}(\text{T})$, the probability of target acceptances in the VG condition. However, a further elaboration of the signal detection model is necessary to accommodate the fact that target recollection has different consequences for target probes than for related distractor probes. Specifically, it is necessary to assume that there are two signal distributions for target recollection, one for target recollection identity (TRI) and one for target recollection contrast (TRC), which correspond to the phenomenologies in the first column of Table 2. For both target and related distractor probes, TRI supports acceptance in V and VG but rejection in G, whereas TRC supports acceptance in G and VG but rejection in V. For targets, the mean of the TRI distribution (μ_{TRI}) is a free parameter, while the mean of the TRC distribution (μ_{TRC}) is fixed at 0. For related distractors, it is the opposite; μ_{TRC} is a free parameter, while $\mu_{TRI} = 0$. With this formulation, the mathematical machinery (see Appendix B) is the same for all probe types. For all three constrained models, the same statistical methods that are described in Appendix B for the unconstrained versions of these models are used to analyze data with the constrained versions. Full developments of the constrained models are presented in the online supplemental materials.

parameters. However, a comprehensive approach was open to us that involved comparing the results reported above when parameters were estimated with the unconstrained models to new results obtained when parameters are reestimated with the constrained models. Above, results were reported for estimates of six parameters, three retrieval parameters for related distractors and three bias/criterion parameters. The question is whether those results change substantially when the parameters are reestimated with the constrained models, which they should not if the restriction is acceptable. That question was addressed with four analyses, each of which was supportive.

First, using the corpus of conjoint recognition data, we computed bivariate correlations between the prior estimates of the six parameters and the reestimates of these parameters. For all three models, the correlations showed that constrained and unconstrained estimates were in close agreement: The mean correlations for the six parameters were .94 for the multinomial model, .94 for the mixed model, and .93 for the signal detection model. Second, using the constrained estimates of the retrieval parameters, we recomputed the earlier G^2 tests of the null hypotheses that the means of the target recollection, context recollection, and familiarity parameters could each be restricted to be zero. For each of the three models, all of these null hypotheses were rejected at high levels of confidence. For each model, we streamlined this analysis by computing one G^2 test for the entire data corpus, with 221 degrees of freedom and a critical value of 256.68. Across the three models, the mean values of G^2 were 867.78, 1,245.89, and 3,988.86 for deleting target recollection, context recollection, and familiarity, respectively, from the models.

Third, we recomputed the earlier factor analyses of the parameter spaces of the unconstrained models. Previously, each model produced a two-factor solution, with the target recollection and bias/criterion parameters loading on one factor and the context recollection and familiarity parameters loading on the other. The factor analyses of the constrained models' estimates of the six parameters produced the same patterns—namely, two-factor solutions, with the same parameters loading on each factor. Fourth, we repeated the earlier analysis of the effects of experimental manipulations on the unconstrained models' parameter estimates for Experiments 1–4. For related distractors, the parametric loci of the effects of the four manipulations with the constrained model were the same as they were with the unconstrained model. For targets, the constrained model indicated that the parametric loci of these manipulations' effect were similar to their loci for related distractors.

Summing up, there was consistent evidence that the restriction we have implemented to obtain identifiable retrieval parameters for the target data of conjoint recognition is acceptable. Consequently, in the remainder of this section, we briefly report new results that were obtained for target and context recollection when those processes were estimated for target data. The dominant theme is that the behavior of parameters that measure these processes for targets is quite similar to what has already been reported for related distractors.

One Recollection or Two?

Is the bivariate conception of recollection necessary for the models to fit target data, as we saw that it is to fit related distractor

data? The constrained versions of the multinomial, mixed, and signal detection models all estimate nine parameters—the six that were estimated before plus target recollection, context recollection, and familiarity parameters for targets. For each of the latter parameters, we tested whether fits were significantly worse when the parameter was fixed at zero, using the conjoint recognition corpus.

We begin with the key question of whether the target side of recollection can be dispensed with for target data. It did not seem so upon first impression because the mean values of the target recollection parameters for the multinomial, mixed, and signal detection models were all well above zero (cf. Table 7). For each model, we computed a corpus-wide test of the null hypothesis that it is zero. The resulting G^2 (221) statistics all exceeded the .05 critical value (256.68) by wide margins: 5,373.72 (multinomial), 4,705.97 (mixed), and 4,661.88 (signal detection).

Next, if the target side of recollection is necessary to account for target data, perhaps the context recollection process can now be dispensed with. Again, it did not seem so upon first impression because the mean values of this parameter for the three models were also well above zero (cf. Table 7). The resulting G^2 (221) tests confirmed this impression, as the test statistics all exceeded the critical value: 339.92 (multinomial), 510.36 (mixed), and 443.70 (signal detection).

Finally, if target and context recollection processes are both necessary, perhaps the familiarity process is no longer needed to account for target data. However, fits were unsatisfactory when the familiarity parameter was removed from each of the models, which can be inferred from the large mean values of these parameters in Table 7. The mean values of the G^2 (221) statistics were 4,619.01 (multinomial), 3,841.09 (mixed), and 6,462.41 (signal detection). Thus, the bottom line for the three retrieval process is the same for target and related distractor data; neither recollection process can be eliminated, nor can familiarity.

Intermodel Parameter Comparisons

Across the data sets in the conjoint recognition corpus, do estimates of the individual retrieval and bias/criterion parameters that are produced by the three constrained models correlate strongly with each other? If they do, this is a very useful outcome

Table 7
Mean Values of the Constrained Dual-Recollection Models' Target Retrieval and Bias/Criterion Parameters for the Corpus of Conjoint Recognition Data

Parameters	Model		
	Multinomial	Mixed	Signal detection
Retrieval			
Target recollection	$R_{TI} = .28$	$R_{TI} = .30$	$\mu_{TRI} = .45$
Context recollection	$R_C = .17$	$\mu_{CR} = .42$	$\mu_{CR} = .29$
Familiarity	$F = .32$	$\mu_F = .59$	$\mu_F = .58$
Bias/criterion			
V condition	$b_V = .19$	$C_V = .76$	$C_V = .26$
G condition	$b_G = .28$	$C_G = .48$	$C_G = .48$
VG condition	$b_{VG} = .29$	$C_{VG} = .67$	$C_{VG} = .59$

Note. V = accept only targets; G = accept only related distractors; VG = accept both targets and related distractors.

because the models will deliver the same results with respect to the process loci of theoretically motivated manipulations. However, such intermodel correlations may not be strong because the models differ dramatically in the degree to which the processes that they measure are treated as discrete or continuous variables. Here, it has often been hypothesized that models that differ in this way may produce different findings (Pazzaglia et al., 2013), although we saw earlier that intermodel correlations for the six parameters of the unconstrained models were very high ($>.90$) and that some similar results have been obtained in simulations of simple recognition models (Batchelder & Alexander, 2013).

The same was true of the constrained versions of our models. For the multinomial model, we computed bivariate correlations between estimates of each of its nine parameters and the corresponding estimates of the mixed and signal detection models. The mean intermodel parameter correlation was .96 (range = .92–.99) for multinomial versus mixed and .95 (range = .89–.99) for multinomial versus signal detection. We computed the same correlations for the mixed versus signal detection models. There, the mean intermodel parameter correlation was .98 (range = .97–1.00). Therefore, across the three models, the various conditions in the conjoint recognition corpus affected their retrieval and bias/criterion parameters in same way because intermodel parameter correlations were very high.

Factor Structure of the Constrained Models

The earlier factor analyses produced the theoretically important result that regardless of model, target and context recollection parameters never loaded on a common factor. All models produced two-factor solutions, with Factor 1 being the target recollection factor (on which bias/criterion parameters also loaded) and Factor 2 being the context recollection factor (on which the familiarity parameter also loaded). We conducted factor analyses of the unconstrained models' parameter spaces to determine whether these basic patterns were preserved, which they were. The statistical details of those analyses were the same as before, but the variables were the nine parameters of each constrained model, rather than the six parameters of the unconstrained models.

The rotated factors and loadings for each model appear in Table 8. The mixed and signal detection models produced factor structures that most strongly recapitulated previous results (cf. Table 5). With respect to the key previous finding that target and context recollection parameters never loaded on a common factor, the target recollection parameters for both targets (R_{TI}) and related distractors (R_{TC}) always loaded together on one factor, and the context recollection parameters for both targets and related distractors always loaded together on another factor. The mixed and signal detection models produced two-factor solutions, in which Factor 1 was again a target recollection factor, on which both target recollection parameters loaded, and Factor 2 was a context recollection factor, on which both context recollection parameters loaded. Also as before, all of the criterion parameters loaded on Factor 1, and the familiarity parameter for related distractors loaded on Factor 2. The only novel result was that the familiarity parameter for related distractors loaded on Factor 1.

The multinomial model produced a three-factor solution, but otherwise, the factor loadings preserved the key features of the earlier results. Factor 1 was again a target recollection factor, on

Table 8
Loadings of the Parameters of the Constrained Dual-Recollection Models

Parameter	Factors		
	Factor 1 (TRI/TRC/bias)	Factor 2 (CR/F)	Factor 3 (CR)
Multinomial model			
Target retrieval			
R_{TI}	-.79		
R_C			.91
F	-.65		
Related distractor retrieval			
R_{TC}	-.77		
R_C		.68	.48
F		.87	
Bias			
b_V	.83		
b_G	.76		
b_{VG}	.80		
Mixed model			
Target retrieval			
R_{TI}	.84		
μ_{CR}		.77	
μ_F	.73		
Related distractor retrieval			
R_{TC}	.68		
μ_{CR}		.83	
μ_F	-.55	.57	
Criterion			
C_V	.88		
C_G	.70		
C_{VG}	.73		.44
Signal detection model			
Target retrieval			
μ_{TRI}	.83		
μ_{CR}		.81	
μ_F	.85		
Related distractor retrieval			
μ_{TRC}	.60		
μ_{CR}		.81	
μ_F	.53	.46	
Criterion			
C_V	.75		
C_G	.79		
C_{VG}	.83		

Note. The factor analyses of the parameter spaces of the constrained multinomial, mixed, and signal detection models accounted for 71%, 64%, and 69% of the variance, respectively. TRI = target recollection-identity; TRC = target recollection-contrast; CR = context recollection; F = familiarity; V = accept only targets; G = accept only related distractors; VG = accept both targets and related distractors.

which both the target recollection parameter for targets and the target recollection parameter for related distractors loaded, together with all three bias parameters and the familiarity parameter for targets. Factor 2 was the same as the earlier Factor 2: The context recollection and familiarity parameters for related distractors loaded on it. Factor 3 was a context recollection factor on which only the two context recollection parameters loaded.

In short, factor analyses of the constrained models' parameter spaces produced further evidence that target recollection and context recollection are functionally independent processes—this

time, simultaneously for target data and related distractor data. Consistent with the earlier factor analyses and the various effects that we have reviewed, conditions that elevate subjects' ability to recollect presented targets vividly do not generally do likewise for their accompanying contextual details because parameters that measure these respective processes did not load on common factors. A question that was of secondary interest in the earlier factor analyses was whether increases in target recollection make decision criteria more conservative, and here, the results were the same as before. All three bias/criterion parameters loaded together with the two target recollection parameters in such a way that as the latter parameters increased, decision criteria became more conservative.

Effects of Manipulations on Retrieval Parameters

Last, we briefly summarize how the constrained models' target retrieval parameters reacted to the manipulations that were previously investigated for related distractor retrieval parameters. Recall that the manipulations in Experiments 1–4 were picture-word, list repetition, divided attention, and deep-shallow encoding. The findings for the constrained models' estimates of the retrieval parameters for targets, which are displayed in Table 9, were similar to those for related distractors. First, with respect to Experiments 1 and 2, pictorial presentation of DRM lists and repeated presentation of such lists both elevated the target recollection parameters of all three models, and pictorial presentation also elevated the familiarity parameter of the signal detection model. Second, with respect to Experiment 3, full attention elevated the context recollection parameters of all three models, and it also elevated the target recollection parameter of all three models. Third, with respect to Experiment 4, deep processing elevated the familiarity parameters of all three models, as it did for related distractors. In addition, it elevated the context recollection parameters of two of the models (multinomial and mixed) and the target recollection parameters of the remaining model.

Conclusions and Discussion

During the course of this article, we have proposed, evaluated, and modeled a bivariate conception of recollection in which one form involves conscious reinstatement of target presentations per se, while the other involves conscious reinstatement of associated contextual details. Traditionally, recollection has been conceptualized as a univariate process in which memory tests provoke conscious reinstatement of some of the contextual details that accompanied target presentations. Although that approach has been a highly productive one, it now seems empirically and theoretically incomplete. On the empirical side, it does not readily explain some well-established effects. The most salient one is that manipulations that have been found, across many R/K studies, to increase recollective support for targets do not consistently decrease false memory, as would be expected by the customary hypothesis that recollection redounds to the benefit of accuracy. On the theoretical side, the univariate approach does not accommodate either the fact that two conceptions of recollection have coexisted for some years in different segments of the memory literature or the fact that the literature contains demonstrations of target-recollection-without-context-recollection and of context-recollection-without-target-recollection.

Table 9
Estimates of the Constrained Dual-Recollection Models' Target Retrieval Parameters for Experiments 1–4

Experiment/condition	Retrieval parameters		
	TRI	CR	F
Multinomial model			
Experiment 1			
Pictures	.69	.13	.32
Words	.25	.17	.33
Experiment 2			
3 presentations	.61	.21	.34
1 presentation	.37	.17	.35
Experiment 3			
Full attention	.35	.28	.37
Divided attention	.09	.01	.39
Experiment 4			
Deep processing	.40	.51	.53
Shallow processing	.36	.23	.38
Mixed model			
Experiment 1			
Pictures	.71	.26	.62
Words	.27	.39	.55
Experiment 2			
3 presentations	.63	.47	.58
1 presentation	.39	.42	.60
Experiment 3			
Full attention	.35	.72	.60
Divided attention	.11	.30	.61
Experiment 4			
Deep processing	.43	.90	.90
Shallow processing	.37	.54	.57
Signal detection model			
Experiment 1			
Pictures	1.19	.14	.74
Words	.38	.24	.56
Experiment 2			
3 presentations	.98	.31	.58
1 presentation	.56	.26	.60
Experiment 3			
Full attention	.46	.55	.49
Divided attention	.16	.16	.59
Experiment 4			
Deep processing	.63	.59	.74
Shallow processing	.52	.40	.50

Note. TRI, CR, and F are the target recollection-identity, context recollection, and familiarity parameters, respectively, of the three models. Reliable differences are shown in bold type.

These limitations of the univariate view of recollection are not widely appreciated, however. A likely reason is that such an appreciation requires forming connections between the recognition literature, where univariate recollection models and R/K studies are concentrated, and the false memory literature, where work on the target recollection idea is concentrated. Another likely reason is that both varieties of recollection support old decisions about targets, thereby making them difficult to separate with the old/new recognition tasks that have long dominated research on recollection.

The aims of this article have been to integrate target and context recollection in a single theoretical principle, to evaluate the principle's explanatory and predictive powers, to implement it in

multinomial and signal detection models, and to answer some elementary questions about the behavior of those models. According to that principle, the dual-recollection hypothesis, recollection is bivariate, with the directions of the two recollections' effects on old/new recognition being the same for targets but different for related distractors. This immediately explains why some manipulations that elevate target recollective support suppress false memory while others foment it, the explanation being that the former elevate target recollection relative to context recollection, whereas the latter have the opposite effect. This explanation derives methodological support from the fact that R/K instructions state that R judgments can be based on either form of recollection. It also predicts other empirical effects that supply independent support. Four examples that are surprising from the standpoint of univariate recollection but are predicted by the dual-recollection hypothesis are release from recollection rejection, the greater stability over time of false memory responses relative to true memory responses, negative correlations between R judgments about targets and false memory responses, and being able to recollect contextual details for targets whose presentation cannot be remembered.

With respect to modeling dual recollection, an important consideration is that theoretical opinion as to whether recollection is a discrete or a continuous process has shifted over time. Although context recollection has been extensively modeled as a threshold process with the process-dissociation and dual process ROC models, compelling arguments have been advanced for regarding it as graded, leading to more recent frameworks such as the sum-difference and continuous dual process models of R/K data. With respect to target recollection, intuition favors regarding it as a discrete process when it comes to conscious awareness of the presentation of individual targets. Intuition may not be a reliable guide, however, and even if recollection of individual targets is discrete, this process could be expressed in a graded manner in false memory designs because the tendency to reject related distractors may increase in proportion to how many targets are recollected.

Owing to such uncertainties, we developed models that treat all processes as discrete or all processes as continuous or treat target recollection as discrete but context recollection and familiarity as continuous. Those models were then applied to the related and unrelated distractor data of a large corpus of conjoint recognition experiments. Fit tests of all of the models and factor analyses of their parameter spaces were consistent with the principle of bivariate recollection: Fit always failed when one or the other recollection process was removed from any of the models but was acceptable when both were present. Despite making contrasting assumptions about discreteness versus continuity, the models did not differ in their respective fits to the data, and their respective estimates of the target recollection, context recollection, familiarity, and bias/criterion parameters were highly correlated ($>.90$). Two other modeling results supported the notion that target recollection and context recollection are functionally distinct processes. First, factor analyses showed that target and context recollection parameters always loaded on different factors. Second, application of the models in false memory studies of manipulations that have been extensively investigated in the R/K literature showed that although all of the manipulations elevate target R judgments, they have different effects on target and context recollection parameters. The particular manipulations that have been

previously found to suppress false memory elevated target recollection relative to context recollection, whereas the manipulations that have been previously found to increase false memory elevated context recollection relative to target recollection.

As the two recollections support the same responses to targets over the conditions of conjoint recognition, it is a more difficult proposition to separate and model them with target data than with distractor data. In particular, models of target data must incorporate restrictions in order to obtain identifiable parameters for both target and context recollection. Fortunately, there is a theoretically motivated restriction that yields expanded versions of the multinomial, mixed, and signal detection models of distractor data that provide identifiable target and context recollection parameters for target data. Moreover, the restriction's acceptability can be tested by rerunning the earlier modeling analyses of distractor data with the expanded model, in order to determine whether the new results depart in major respects from the previous results. In the event, the two sets of results were in close agreement on four dimensions: values of parameter estimates, fit tests of the necessity of target and context recollection processes, factor structure of parameter spaces, and the parametric loci of treatment effects. When the expanded models were then used to investigate target and context recollection for target data, the empirical picture was very similar to the picture for distractor data: (a) Fit tests showed that both recollection processes were required to account for target data, (b) intermodel parameter correlations showed that the three model's respective estimates of all parameters were highly correlated, (c) factor analyses of the models' parameter spaces revealed that target recollection parameters for related distractor and target data loaded together on the same factor and that context recollection parameters for both types of data loaded together on a different factor, and (d) the parametric loci of the effects of experimental manipulations were the same when target and context recollection parameters were estimated for target data versus distractor data.

To conclude, the case for a bivariate conception of recollection currently rests on four main lines of evidence. First, there are established empirical effects that lie outside the scope of the alternative univariate conception. Second, such effects can be explained by a dual-recollection hypothesis that posits two forms of recollection that have already been foci of research in different segments of the memory literature. Third, this hypothesis predicts other established empirical effects, some of them counterintuitive. Fourth, the two recollections can be implemented in multinomial models, signal detection models, and mixed multinomial/signal detection models, and various results for those models converge on the notion of distinct target and context recollection processes.

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(Appendices follow)

Appendix A

Data Corpora

We assembled three corpora of data: 369 data sets of remember/know (R/K) data for false memory for occurrence designs, 600 sets of R/K data for simple old/new recognition designs, and 221 sets of data for conjoint recognition designs. The data in the first two corpora were used to test certain qualitative predictions of the dual-recollection hypothesis. The data in the third corpus were used to conduct modeling analyses—explicitly, to fit the three dual-recollection models, to estimate their parameters, to determine the factor structure of their parameter spaces, and to pinpoint the process loci of experimental manipulations.

The first corpus contained data from false memory experiments. It consisted of all published data sets that we were able to locate in which R/K judgments had been made as part of old/new recognition tests in false memory for occurrence designs. Thus, in such experiments, R/K judgments were made about old responses to targets, related distractors, and unrelated distractors. There were 369 data sets in all, consisting of 266 data sets in which Deese–Roediger–McDermott lists were used to measure false memory for occurrence and 103 data sets in which various other types of materials were used (e.g., categorized word lists, emotional word lists, pictures of familiar objects, narratives, videos). The subjects were undergraduates for the most part, but older adult subjects participated in some studies. Also, some of the classic content and procedural manipulations in the mainstream R/K literature (which was the focus of the second corpus) were present in this false memory corpus, such as deep versus shallow encoding, emotional versus neutral lists, fast versus slow presentation, full versus divided attention, generate versus read encoding, immediate versus delayed testing, interpolation of different buffer activities, picture versus word lists, and list length.

The second corpus contained data from traditional, mainstream R/K experiments of the type that was discussed at the outset of the article. In other words, whereas the first corpus contained data in which subjects made old/new decisions about three types of probes (targets, related distractors, unrelated distractors) and made R/K judgments following old decisions, the second corpus contained data in which subjects made old/new decisions about two types of probes (target, unrelated distractors) and made R/K judgments following old decisions. Approximately half of these data sets came from three corpora that were previously assembled by Donaldson (1996), Dunn (2008), and Rotello et al. (2004), respectively. We eliminated some data sets from their corpora for various reasons, the most important of which were that they did not meet

one or both of two requirements: (a) The subjects had learned the target material to a reasonable level of accuracy, and (b) tests of false memory for related distractor materials had *not* been administered. In particular, we eliminated all data sets for which the hit rate was not at least .10 greater than the false alarm rate, and we eliminated all data sets that were from false memory for occurrence experiments (e.g., Lampinen et al., 2001). (The latter data sets were placed in the first corpus.) We then added more than 300 further data sets from recently published R/K experiments that met these requirements, to bring the total to 600. The study lists consisted of unrelated words for the most part, but pictures of objects, pictures of faces, sentences, and nonsense strings were used in some studies. Similar to the first corpus, the subjects were undergraduates for the most part, but older adult subjects participated in some studies. The corpus encompassed all of the classic content and procedural manipulations that are known to affect the probability of R and K judgments as well as the accuracy of old/new recognition, such as fast versus slow list presentation, fast versus slow testing, immediate versus delayed testing, interpolation of different buffer activities between study and test, single versus multiple presentation of lists, studying high- versus low-frequency word lists, studying emotional versus neutral word lists, studying lists under deep versus shallow encoding instructions, studying lists under full versus divided attention, studying lists under generate versus read instructions, studying picture versus word lists, and studying short versus long lists.

The third corpus consisted of 221 sets of conjoint recognition data, which were all of the published data sets that we were able to locate, as well as some unpublished sets that had been reported at conferences. All of these data sets were from experiments in which the three instructional conditions of conjoint recognition were added to the usual false memory for occurrence design. Although the target materials were word lists in the preponderance of experiments, there was also a substantial number of data sets (72) in which the target materials were sentence lists or narratives. As in the first two corpora, the subjects in most experiments were young adults, but a substantial number of these data sets (40) involved child subjects. Last, although the preponderance of data sets involved immediate tests that were administered within a few minutes of studying the target materials (as in the first two corpora), a substantial number (96) involved delayed tests that were administered a few days to a week after target materials were studied.

(Appendices continue)

Appendix B

Dual-Recollection Models for Conjoint Recognition

Three models were used to fit and analyze related distractor (RD) data from the conjoint recognition corpus: a multinomial model (see Figure 3 in the main text), a mixed multinomial and signal detection model (see Figure 4 in the main text), and a signal detection model (see Figure 5 in the main text). Statistical methods for the multinomial model are presented first, followed by statistical methods for the mixed and signal detection models, followed by goodness-of-fit tests for all three models. The software for these models can be downloaded at <http://www.human.cornell.edu/hd/brainerd/research.cfm>.

Multinomial Model

The multinomial model differs from the signal detection and mixed models in that target recollection, context recollection, and familiarity are all assumed to be discrete rather than continuous processes. When an RD is presented during test, it may cause target recollection to occur with some probability R_{TC} , or it may not with probability $(1 - R_{TC})$. When target recollection fails, context recollection may occur with some probability R_C , or it may not with probability $(1 - R_C)$. When target recollection and context recollection fail, familiarity may occur with some probability F , or it may not with probability $(1 - F)$. Across the instructional conditions of conjoint recognition, target recollection, context recollection, and familiarity produce acceptance or rejection of RDs in accordance with the rules in Table 2 in the main text. When target recollection, context recollection, and familiarity fail, response bias may occur and produce probe acceptance with some probability b_j in instructional condition $j = \{V, G, VG\}$, or it may not and the probe may be rejected with probability $(1 - b_j)$.

Thus, the multinomial model has six free parameters, all of which can be identified in the outcome spaces of conjoint recognition experiments because a minimum of six degrees of freedom are available. These parameters can be estimated, fit tests can be conducted, and parameter comparison analyses can be conducted with conjoint recognition data using the likelihood function

$$\begin{aligned}
 L_6 = & [(1 - R_{TC})R_C - (1 - R_{TC})(1 - R_C)F - (1 - R_{TC})(1 - R_C)(1 - F)b_V]^{A(RD,V)} \\
 & \times [1 - (1 - R_{TC})R_C - (1 - R_{TC})(1 - R_C)F - (1 - R_{TC})(1 - R_C)(1 - F)b_V]^{R(RD,V)} \\
 & \times [R_{TC} + (1 - R_{TC})(1 - R_C)F + (1 - R_{TC})(1 - R_C)(1 - F)b_G]^{A(RD,G)} \\
 & \times [1 - R_{TC} - (1 - R_{TC})(1 - R_C)F - (1 - R_{TC})(1 - R_C)(1 - F)b_G]^{R(RD,G)} \\
 & \times [R_{TC} + (1 - R_{TC})R_C + (1 - R_{TC})(1 - R_C)F + (1 - R_{TC})(1 - R_C)(1 - F)b_{VG}]^{A(RD,VG)} \\
 & \times [1 - R_{TC} - (1 - R_{TC})R_C - (1 - R_{TC})(1 - R_C)F - (1 - R_{TC})(1 - R_C)(1 - F)b_{VG}]^{R(RD,VG)} \\
 & \times (b_V)^{A(UD,V)} \times (1 - b_V)^{R(UD,V)} \times (b_G)^{A(UD,G)} \times (1 - b_G)^{R(UD,G)} \times (b_{VG})^{A(UD,VG)} \times (1 - b_{VG})^{R(UD,VG)},
 \end{aligned}
 \tag{B1}$$

in which the exponents $A(i, j)$ and $R(i, j)$ are, respectively, the acceptance and rejection frequencies for the probe $i = \{RD, UD\}$ and instructional condition $j = \{V, G, VG\}$.

Three technical points about the multinomial model should be noted. First, in addition to the target recollection process for RDs, which is measured by R_{TC} , there is another such process for T (target) probes that generates identify/match phenomenology. Even if the model were defined over T as well RD and unrelated distractor (UD) probes, identifiable estimates of this other process could not be secured because in the conjoint recognition paradigm, target and context recollection produce the same T responses in all three conditions (cf. Table 2 in the main text). However, identifiable estimates can be obtained with a constrained version of this model (see the section Modeling Dual-Recollection Processes With Target Data in the main text).

Second, UDs are assumed to measure response bias only and not to also access a familiarity process. That is a standard assumption in multinomial dual process models of recognition, with Jacoby's (1991) process-dissociation model and its variants and Batchelder and Riefer's (1990) source-monitoring model and its variants being well-known examples. If it were assumed instead that UD performance is controlled by familiarity as well as response bias, it would be necessary to include a familiarity parameter for UDs in the model. That, however, would have the highly undesirable consequence of rendering the model nonidentifiable because there would be seven parameters to estimate (four memory parameters and three bias parameters) with only six empirical probabilities.

Third, for simple old/new recognition, it has been suggested by some that threshold models may produce erroneous estimates of memory parameters when response bias varies (see Pazzaglia et al., 2013). Although the present model is a threshold model, it does not follow that conclusions about old/new recognition apply to other paradigms, such as conjoint recognition, process dissociation, or source monitoring (Batchelder & Alexander, 2013). Nevertheless, we evaluated this possibility by conducting simulations of the model's parameter space under variations in its bias parameters. These simulations failed to reveal any tendency for estimates of its memory parameters (R_{TC} , R_C , and F) to be systematically biased by variations in the values of its bias parameters.

(Appendices continue)

Mixed and Signal Detection Models

For continuous variables, the mixed and signal detection models assume that recognition decisions are made according to the placement of an internal response criterion that divides a combination of process distributions into two regions, one in which the test probe is accepted and another in which it is rejected. This assumption is formalized next for each model.

Dual-Recollection Signal Detection Model

In the signal detection model, target recollection, context recollection, and familiarity are all assumed to be independent and normally distributed processes. Specifically, let the probability density distributions of the target recollection, context recollection, and familiarity processes for RDs be $\varphi(\mu_{TRC|i}, \sigma_{TRC|i})$, $\varphi(\mu_{CR|i}, \sigma_{CR|i})$, and $\varphi(\mu_{F|i}, \sigma_{F|i})$, $i = \{RD, UD\}$, in which $\varphi(\mu, \sigma)$ is a Gaussian probability density function with mean μ and standard deviation σ . For RDs, the combination of process distributions under each instructional condition is given by the following expression:

$$h_{j|RD} = \begin{cases} \varphi\left(\mu_{CR|RD} - \mu_{TRC|RD} + \mu_{F|RD}, \sqrt{\sigma_{TRC|RD}^2 + \sigma_{CR|RD}^2 + \sigma_{F|RD}^2}\right) & j = V \\ \varphi\left(\mu_{TRC|RD} - \mu_{CR|RD} + \mu_{F|RD}, \sqrt{\sigma_{TRC|RD}^2 + \sigma_{CR|RD}^2 + \sigma_{F|RD}^2}\right) & j = G \\ \varphi\left(\mu_{TRC|RD} + \mu_{CR|RD} + \mu_{F|RD}, \sqrt{\sigma_{TRC|RD}^2 + \sigma_{CR|RD}^2 + \sigma_{F|RD}^2}\right) & j = VG \end{cases} \quad (B2)$$

as the sums and differences of independent Gaussian distributions is also a Gaussian distribution. For UD, we assume that $\mu_{TRC|UD} = \mu_{CR|UD} = \mu_{F|UD} = 0$, and thus, its distribution is the following regardless of linear combination among process distributions:

$$h_{j|UD} = \varphi\left(0, \sqrt{\sigma_{TRC|UD}^2 + \sigma_{CR|UD}^2 + \sigma_{F|UD}^2}\right) \quad j = \{V, G, VG\}. \quad (B3)$$

Using Equations B2 and B3, the predicted response probabilities can be expressed as functions of model parameters. As before, the model assumes that the combinations of process distributions in Equations B2 and B3 are partitioned into two regions (acceptance/rejection) according to internal response criteria. More specifically, the acceptance probability of instructional condition j given the test probe i is

$$\Pr(S \geq C_j | i) = \int_{C_j}^{\infty} h_{ji}(s) ds, \quad (B4)$$

in which S is an overall memory strength variable, whereas the rejection probability of instructional condition j given test probe i is simply the complement of Equation B4:

$$\Pr(S < C_j | i) = \int_{-\infty}^{C_j} h_{ji}(s) ds = 1 - \Pr(S \geq C_j | i). \quad (B5)$$

Therefore, for RDs, Equation B4 is

$$\Pr(S \geq C_j | RD) = \begin{cases} \Phi\left(\frac{\mu_{CR|RD} - \mu_{TRC|RD} + \mu_{F|RD} - C_V}{\sqrt{\sigma_{TRC|RD}^2 + \sigma_{CR|RD}^2 + \sigma_{F|RD}^2}}\right) & j = V \\ \Phi\left(\frac{\mu_{TRC|RD} - \mu_{CR|RD} + \mu_{F|RD} - C_G}{\sqrt{\sigma_{TRC|RD}^2 + \sigma_{CR|RD}^2 + \sigma_{F|RD}^2}}\right) & j = G \\ \Phi\left(\frac{\mu_{TRC|RD} + \mu_{CR|RD} + \mu_{F|RD} - C_{VG}}{\sqrt{\sigma_{TRC|RD}^2 + \sigma_{CR|RD}^2 + \sigma_{F|RD}^2}}\right) & j = VG \end{cases} \quad (B6)$$

(Appendices continue)

in which $\Phi(\cdot)$ is the Gaussian cumulative distribution function. For UDs, Equation B4 is

$$\Pr(S \geq C_j | UD) = \begin{cases} \Phi\left(-\frac{C_V}{\sqrt{\sigma_{TRCUD}^2 + \sigma_{CRIUD}^2 + \sigma_{FUD}^2}}\right) & j = V \\ \Phi\left(-\frac{C_G}{\sqrt{\sigma_{TRCUD}^2 + \sigma_{CRIUD}^2 + \sigma_{FUD}^2}}\right) & j = G \\ \Phi\left(-\frac{C_{VG}}{\sqrt{\sigma_{TRCUD}^2 + \sigma_{CRIUD}^2 + \sigma_{FUD}^2}}\right) & j = VG \end{cases} \quad (B7)$$

Equations B6 and B7 have a total of 12 free parameters, where traditional conjoint recognition experiments generate either six or nine degrees of freedom, depending on design details (see Brainerd et al., 2001), so that identifiable estimates of all the free parameters cannot be obtained. However, the number of free parameters can be reduced by half using procedures that are common in the literature on signal detection models—namely, by assigning constant values to the standard deviation of the distributions of RDs ($\sqrt{\sigma_{TRCIRD}^2 + \sigma_{CRIIRD}^2 + \sigma_{FIRD}^2}$) and UDs ($\sqrt{\sigma_{TRCUD}^2 + \sigma_{CRIUD}^2 + \sigma_{FUD}^2}$). This yields a signal detection model with six identifiable free parameters (μ_{TRCIRD} , μ_{CRIIRD} , μ_{FIRD} , C_V , C_G , and C_{VG}) that can be estimated from RD and UD data. This can be done with any of the usual optimization methods (e.g., simplex, expectation-maximization, or gradient algorithms) by maximizing the following likelihood function:

$$\begin{aligned} L_6 &= \prod_{i,j} \Pr(S \geq C_j | i)^{A(i,j)} \Pr(S < C_j | i)^{R(i,j)} \\ &= \Phi\left(\frac{\mu_{CRIIRD} - \mu_{TRCIRD} + \mu_{FIRD} - C_V}{\sqrt{\sigma_{TRCIRD}^2 + \sigma_{CRIIRD}^2 + \sigma_{FIRD}^2}}\right)^{A(RD,V)} \times \left(1 - \Phi\left(\frac{\mu_{CRIIRD} - \mu_{TRCIRD} + \mu_{FIRD} - C_V}{\sqrt{\sigma_{TRCIRD}^2 + \sigma_{CRIIRD}^2 + \sigma_{FIRD}^2}}\right)\right)^{R(RD,V)} \\ &\times \Phi\left(\frac{\mu_{TRCIRD} - \mu_{CRIIRD} + \mu_{FIRD} - C_G}{\sqrt{\sigma_{TRCIRD}^2 + \sigma_{CRIIRD}^2 + \sigma_{FIRD}^2}}\right)^{A(RD,G)} \times \left(1 - \Phi\left(\frac{\mu_{TRCIRD} - \mu_{CRIIRD} + \mu_{FIRD} - C_G}{\sqrt{\sigma_{TRCIRD}^2 + \sigma_{CRIIRD}^2 + \sigma_{FIRD}^2}}\right)\right)^{R(RD,G)} \\ &\times \Phi\left(\frac{\mu_{TRCIRD} + \mu_{CRIIRD} + \mu_{FIRD} - C_{VG}}{\sqrt{\sigma_{TRCIRD}^2 + \sigma_{CRIIRD}^2 + \sigma_{FIRD}^2}}\right)^{A(RD,VG)} \times \left(1 - \Phi\left(\frac{\mu_{TRCIRD} + \mu_{CRIIRD} + \mu_{FIRD} - C_{VG}}{\sqrt{\sigma_{TRCIRD}^2 + \sigma_{CRIIRD}^2 + \sigma_{FIRD}^2}}\right)\right)^{R(RD,VG)} \\ &\times \Phi\left(-\frac{C_V}{\sqrt{\sigma_{TRCUD}^2 + \sigma_{CRIUD}^2 + \sigma_{FUD}^2}}\right)^{A(UD,V)} \times \left(1 - \Phi\left(-\frac{C_V}{\sqrt{\sigma_{TRCUD}^2 + \sigma_{CRIUD}^2 + \sigma_{FUD}^2}}\right)\right)^{R(UD,V)} \\ &\times \Phi\left(-\frac{C_G}{\sqrt{\sigma_{TRCUD}^2 + \sigma_{CRIUD}^2 + \sigma_{FUD}^2}}\right)^{A(UD,G)} \times \left(1 - \Phi\left(-\frac{C_G}{\sqrt{\sigma_{TRCUD}^2 + \sigma_{CRIUD}^2 + \sigma_{FUD}^2}}\right)\right)^{R(UD,G)} \\ &\times \Phi\left(-\frac{C_{VG}}{\sqrt{\sigma_{TRCUD}^2 + \sigma_{CRIUD}^2 + \sigma_{FUD}^2}}\right)^{A(UD,VG)} \times \left(1 - \Phi\left(-\frac{C_{VG}}{\sqrt{\sigma_{TRCUD}^2 + \sigma_{CRIUD}^2 + \sigma_{FUD}^2}}\right)\right)^{R(UD,VG)}, \end{aligned} \quad (B8)$$

in which $A(i, j)$ is the acceptance frequency and $R(i, j)$ is the rejection frequency of item $i = \{RD, UD\}$ under instruction $j = \{V, G, VG\}$.

Dual-Recollection Mixed Multinomial/Signal Detection Model

The mixed model differs from the signal detection model in that target recollection is assumed to be a discrete process rather than a continuous one. More specifically, when a probe is presented during test, it may cause target recollection to occur with some probability R_{TC} , or it may not with probability $(1 - R_{TC})$. When target recollection fails, recognition is based on internal response criteria that partition convolutions of the remaining process distributions (context recollection and familiarity) into acceptance/rejection regions. For RDs, the combination of process distributions under each instructional condition is

$$h_{j|RD} = \begin{cases} \varphi(\mu_{CRIIRD} + \mu_{FIRD}, \sqrt{\sigma_{CRIIRD}^2 + \sigma_{FIRD}^2}) & j = V \\ \varphi(\mu_{FIRD} - \mu_{CRIIRD}, \sqrt{\sigma_{CRIIRD}^2 + \sigma_{FIRD}^2}) & j = G \\ \varphi(\mu_{CRIIRD} + \mu_{FIRD}, \sqrt{\sigma_{CRIIRD}^2 + \sigma_{FIRD}^2}) & j = VG \end{cases} \quad (B9)$$

(Appendices continue)

For UD_s, the combination of process distributions is

$$h_{jUD} = \phi\left(0, \sqrt{\sigma_{CRUD}^2 + \sigma_{FUD}^2}\right) \quad j = \{V, G, VG\}. \tag{B10}$$

Consequently, the predicted acceptance probability of instructional condition j given that the test probe is an RD is

$$\Pr(\text{Accept} \mid RD) = \begin{cases} (1 - R_{TC})\Phi\left(\frac{\mu_{CRIRD} + \mu_{FIRD} - C_V}{\sqrt{\sigma_{CRIRD}^2 + \sigma_{FIRD}^2}}\right) & j = V \\ R_{TC} + (1 - R_{TC})\Phi\left(\frac{\mu_{FIRD} - \mu_{CRIRD} - C_G}{\sqrt{\sigma_{CRIRD}^2 + \sigma_{FIRD}^2}}\right) & j = G \\ R_{TC} + (1 - R_{TC})\Phi\left(\frac{\mu_{CRIRD} + \mu_{FIRD} - C_{VG}}{\sqrt{\sigma_{CRIRD}^2 + \sigma_{FIRD}^2}}\right) & j = VG \end{cases} \tag{B11}$$

in which S is an overall memory strength variable, whereas the predicted acceptance probability of instructional condition j given that the test probe is a UD is

$$\Pr(\text{Accept} \mid UD) = \begin{cases} \Phi\left(-\frac{C_V}{\sqrt{\sigma_{CRUD}^2 + \sigma_{FUD}^2}}\right) & j = V \\ \Phi\left(-\frac{C_G}{\sqrt{\sigma_{CRUD}^2 + \sigma_{FUD}^2}}\right) & j = G \\ \Phi\left(-\frac{C_{VG}}{\sqrt{\sigma_{CRUD}^2 + \sigma_{FUD}^2}}\right) & j = VG \end{cases} \tag{B12}$$

Equations B11 and B12 have a total of 10 free parameters, which cannot all be uniquely identified in the outcome spaces of traditional conjoint recognition designs. By applying the same assumptions as the ones described for the dual-recollection signal detection model, however, the number of free parameters can be reduced to six, all of which are identifiable—namely, R_{TC} , μ_{CRIRD} , μ_{FIRD} , C_V , C_G , and C_{VG} . These parameters can be estimated, fit tests can be conducted, and parameter comparison analyses can be conducted with conjoint recognition data using the following likelihood function:

$$\begin{aligned} L_6 = & (1 - R_{TC})\Phi\left(\frac{\mu_{CRIRD} + \mu_{FIRD} - C_V}{\sqrt{\sigma_{CRIRD}^2 + \sigma_{FIRD}^2}}\right)^{A(RD,V)} \times \left(1 - (1 - R_{TC})\Phi\left(\frac{\mu_{CRIRD} + \mu_{FIRD} - C_V}{\sqrt{\sigma_{CRIRD}^2 + \sigma_{FIRD}^2}}\right)\right)^{R(RD,V)} \\ & \times \left(R_{TC} + (1 - R_{TC})\Phi\left(\frac{\mu_{FIRD} - \mu_{CRIRD} - C_G}{\sqrt{\sigma_{CRIRD}^2 + \sigma_{FIRD}^2}}\right)\right)^{A(RD,G)} \times \left(1 - R_{TC} - (1 - R_{TC})\Phi\left(\frac{\mu_{FIRD} - \mu_{CRIRD} - C_G}{\sqrt{\sigma_{CRIRD}^2 + \sigma_{FIRD}^2}}\right)\right)^{R(RD,G)} \\ & \times \left(R_{TC} + (1 - R_{TC})\Phi\left(\frac{\mu_{CRIRD} + \mu_{FIRD} - C_{VG}}{\sqrt{\sigma_{CRIRD}^2 + \sigma_{FIRD}^2}}\right)\right)^{A(RD,VG)} \times \left(1 - R_{TC} - (1 - R_{TC})\Phi\left(\frac{\mu_{CRIRD} + \mu_{FIRD} - C_{VG}}{\sqrt{\sigma_{CRIRD}^2 + \sigma_{FIRD}^2}}\right)\right)^{R(RD,VG)} \\ & \times \Phi\left(-\frac{C_V}{\sqrt{\sigma_{CRUD}^2 + \sigma_{FUD}^2}}\right)^{A(UD,V)} \times \left(1 - \Phi\left(-\frac{C_V}{\sqrt{\sigma_{CRUD}^2 + \sigma_{FUD}^2}}\right)\right)^{R(UD,V)} \\ & \times \Phi\left(-\frac{C_G}{\sqrt{\sigma_{CRUD}^2 + \sigma_{FUD}^2}}\right)^{A(UD,G)} \times \left(1 - \Phi\left(-\frac{C_G}{\sqrt{\sigma_{CRUD}^2 + \sigma_{FUD}^2}}\right)\right)^{R(UD,G)} \\ & \times \Phi\left(-\frac{C_{VG}}{\sqrt{\sigma_{CRUD}^2 + \sigma_{FUD}^2}}\right)^{A(UD,VG)} \times \left(1 - \Phi\left(-\frac{C_{VG}}{\sqrt{\sigma_{CRUD}^2 + \sigma_{FUD}^2}}\right)\right)^{R(UD,VG)} \end{aligned} \tag{B13}$$

(Appendices continue)

Goodness-of-Fit Tests

Note that the likelihood functions in Equations B1, B8, and B13 are saturated. The goodness-of-fit tests that we reported for the single-recollection and pure recollection models were all conducted by imposing one or more constraints on the freedom of the six free parameters to vary in the multinomial, mixed, and signal detection versions of the dual-recollection model. Under such constraints, new values of the likelihood functions in Equations B1, B8, and B13 are calculated, which are denoted L_{6-k} , where k is the number of constraints. Therefore, to evaluate fit or conduct parameter significance tests, the test statistic was

$$G^2(k) = -2 \ln \left(\frac{L_{6-k}}{L_6} \right), \quad (\text{B14})$$

which is asymptotically distributed as $\chi^2(k)$.

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