A CONTINUOUS DUAL-PROCESS ACCUMULATION MODEL OF RECOGNITION JUDGMENTS

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ABSTRACT OF THE DISSERTATION

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Theories of recognition have shifted from a single process approach to a dual-process view, which distinguishes between knowing that one has experienced an object before (familiarity) and knowing what it was (recollection). The remember/know procedure, in which remember judgments are assumed to reflect recollection and know judgments are assumed to be based on familiarity, is widely used to investigate these two processes. While most recent dual process models can account for relationships among accuracy, remember/know judgments, and study factors that influence recognition (under a range of different assumptions), none of these models address the time course of the recognition process. As a results, paradoxical findings that familiarity is available faster than recollection but remember responses are on average faster than know responses, cannot be convincingly explained by any existing dual process model.

In this dissertation, we resolve this paradox by proposing an elaborated dual process model of recognition called the Continuous Dual Process Accumulation (CDPA) model. The CDPA model uses the dual-system hypothesis of mammalian memory (Packard and McGaugh, 1996) as its neurological basis, describing the interplay between the hippocampus and the caudate in making recognition judgments, which allows it to make detailed predictions regarding

the time course of recollection and familiarity, and explain how the information available through these two processes is applied to make the recognition decision .

In the first half of the dissertation, a neuro-imaging study is presented, which tests a key assumption of the CDPA model that quick familiarity signals are based on perceptual judgments produced by the instrumental system (which includes the hippocampus), while the slower recollection signals require the habit system (which includes the caudate nucleus of the striatum) to generate the memory trace. The second half presents the CDPA model, which is implemented computationally as a collapsing bound diffusion model. A conventional recognition task for previously studied words is used to test the predictions of the model qualitatively and quantitatively. The model therefore extends signal detection theory, and allows, for the first time, predictions of hits and false alarms for remember and know judgments based on confidence, accuracy *and RT*.

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Dedication

To my grandfather for being such an inspiration.

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1. Introduction

Recognition occurs so rapidly that the processes that make it possible remain mysterious. Most of us have experienced encountering a person whom we are certain we know, but are unable to place, until we glimpse the nametag. At that moment, we are suddenly flooded with details about the person, the time we met, and our prior mutual history. These intuitions suggest that knowing an item was previously encountered versus remembering details of the encounter itself are the result of separate mental processes.

For the past 40 years it has been debated whether recognition memory is best understood as a single process or a dual process (familiarity and recollection). The development of signal detection theory in the 1950's made it possible to accurately measure recognition memory. It was based on the important insight that recognition was a continuous judgment for which a criterion was set. However, two limitations of signal detection theory were that it assumed a single process model and it did not include a method for analyzing the accumulation of information over time. In 1960s reaction time was reintroduced as a method for studying how information accumulated during recognition. The application of this method immediately produced a paradox suggesting that two distinct kinds of information, hence two distinct processes were involved in recognition, recollection and familiarity. This was the dual process hypothesis.

Despite its central role in the initial consideration of the dual process hypothesis, in subsequent decades RT was abandoned as a measure. Theories of recognition were evaluated by measuring accuracy within the framework of signal detection theory. Nevertheless, with the introduction of the categorization of recognition as remember versus know judgments as measures of recollection versus familiarity, respectively, evidence accumulated in favor the of the dual process hypothesis. Dual process models therefore began to gain in favor in the mid 1990s and by the beginning of the millennium, recognition memory was widely viewed to consist of recollection and familiarity.

Research during these decades was devoted to deciding among a variety of versions of the dual process hypothesis. One issue which has been the subject of much debate is whether recollection and familiarity serve as independent bases for recognition judgment (segregated) or whether they are combined to produce a single memory strength variable (integrated) that serves as the basis of recognition judgments. This debate between a segregated versus integrated view of recognition judgment is not yet settled. In fact, the boundaries between segregated and integrated models have become increasingly blurred. One reason for this lack of consensus in the field is that none of the recent models make predictions that converge across all the measures that have been developed to assess recollection and familiarity, namely confidence, accuracy, remember/know and response time.

This dissertation attempts to settle the segregated versus integrated debate by proposing a new integrated dual process model of recognition called the Continuous Dual Process Accumulation Model (CDPA), which extends signal detection theory to account for RT, and allows, for the first time, predictions of hits and false alarms for remember and know judgments based on confidence, accuracy *and RT*. The CDPA is a model that integrates the dual system hypothesis of memory (Packard and McGaugh, 1996) with the dual processes model of recognition. It predicts how familiarity and recollection information is retrieved over time, therefore explaining the proportion of correct responses and RT distributions for remember and know judgments in each confidence category.

1.1 Outline

The remainder of this dissertation is organized as follows.

- **Chapter 2** provides a discussion of relevant research and theory to the CDPA model. First is a review of empirical results that decisively support a dual process account of recognition memory. Next, the two conflicting classes of dual process theories (segregated versus integrated) are described in detail and the empirical results that differentiate between them are reviewed. This is followed by a detailed analysis of individual segregated and integrated dual process models within the context of experimental results.
- **Chapter 3** presents an experiment that tested the key assumption of the CDPA model, familiarity is generated by a neural system that includes the hippocampus and recollection is generated by a neural system that includes the caudate nucleus of the striatum. The experiment made use of a task in which two four letter strings were presented in quick succession, and participants had to respond as rapidly as possible whether they were the *same* or *different*. The two strings that formed a *same* pair were identical (i.e., the strings contained the same letters in the same order), whereas the strings that formed a *different* pair had the same letters, but in different orders. As will be discussed, the CDPA model predicts that *same* responses are associated with hippocampus activation and *different* responses are associated with both hippocampus and caudate activation. fMRI was used to measure activation.

- **Chapter 4** presents a quantitative version of the CDPA model and tests its predictions using a conventional word recognition task. In this task, subjects were presented with a study list and were later presented with a longer test list and asked to respond as rapidly as possible which words were on the study list, i.e., whether each word is old or new. Speeded old/new decisions were followed by confidence ratings, remember/know judgments and source judgments. RT, decision accuracy and source accuracy for remember and know responses in each confidence category were evaluated to verify the predictions of the CDPA model.
- **Chapter 5** discusses the relevance of our findings, and proposes directions for future research.

2. Theories of Recognition

This chapter attempts to condense decades of research on dual process models, highlighting previous models and empirical results that have informed the work presented in this dissertation. The chronological development of dual process theory is described and results that support a dual process account of recognition memory are presented. The issue of whether familiarity and recollection are two segregated independent memory processes or an integrated single process reflecting a continuum of memory strength is addressed, with a general discussion of the segregated versus integrated classes of dual process theories within the context of experimental data. Finally, individual (segregated and integrated) dual process models are described and analyzed in detail.

2.1Signal Detection Theory

Phenomenologically, recognition is an extension of perception. We not only see or hear something, but immediately recognize what it is as well. Therefore, it is unsurprising that the first modern theory of recognition was the first modern theory of perception. Signal detection theory, originally developed to measure perceptual thresholds, was extended to recognition as well.

Recognition models based on signal detection theory are single process models (Swets, Tanner, and Birdsall, 1961; Tanner and Swets, 1954). They assume that recognition decisions are based on a continuous, one-dimensional memory strength variable that reflects a singular process like familiarity. As shown in Figure 2.1, the prototypical version of a single process model involves two equal variance Gaussian distributions (one representing targets and the other representing distracters) and one

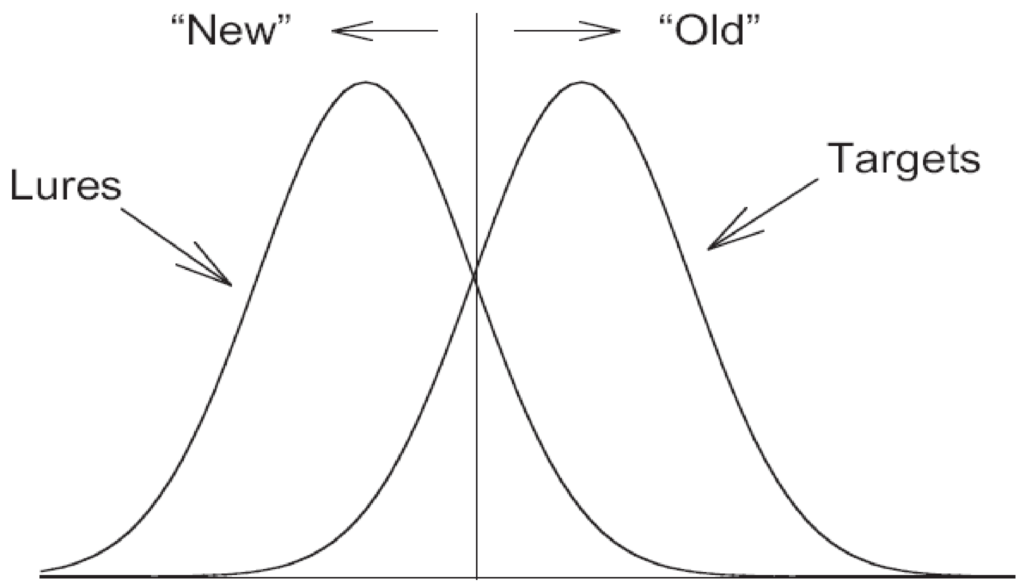

Figure 2.1. The equal variance signal detection (EVSD) model assumes that the variance associated with the target items is equal to that associated with the distracters.

decision criterion. The equal variance signal detection (EVSD) model is the simplest signal detection model. It assumes that the variance associated with the target items is equal to that associated with the distracters. Any test item that generates a memory strength exceeding a criterion is declared to be old; otherwise it is declared to be new. Hence, recognition decisions are made by setting a response criterion and responding old to all items exceeding that criterion. This model is deterministic in the sense that it assumes that there is a relevant memory signal for every test item, whether the item is old or new.

Although the equal-variance detection model is often used to illustrate single process models, much evidence suggests that a quantitatively more accurate version of the theory is an unequal variance model, as shown in Figure 2.2, in which the standard deviation of the target distribution somewhat exceeds that of the distracter distribution (Egan, 1958; Ratcliff, Sheu, and Gronlund, 1992). It might seem that the unequal

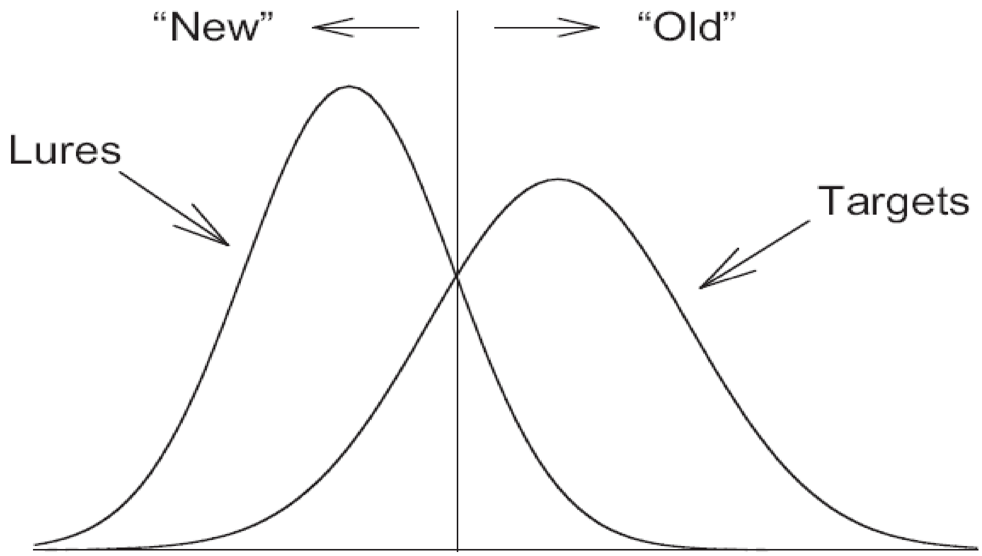

Figure 2.2. The unequal variance signal detection (UVSD) model assumes that the variance of the target distribution exceeds that of the distracter distribution.

variance model is inherently less plausible than the more aesthetically appealing equal-variance model, but the opposite is actually true. The targets can be thought of as distracters that have had memory strength added to them by virtue of their appearance on the study list. An equal variance model would result if each item on the list had the exact same amount of strength added during study. However, if the amount of strength that is added differs across items, which surely must be the case, then both strength and variability would be added, and an unequal variance model would apply. Thus, it is actually the equal variance model that is, a priori, the less plausible account. Hence, traditionally, single process models are conceptualized in terms of a Gaussian unequal variance signal detection (UVSD) model (Egan, 1958).

Signal detection theory was originally developed to account for the accuracy of perceptual and recognition judgments. A weakness in using signal detection theory to assess accuracy was that while it allowed evaluation of the kinds of features that were compared when a test item was compared with a memory representation, it did not make predictions about the order in which features were compared. This temporal aspect of the comparison process was entirely absent from the analysis provided by signal detection theory.

2.2 Reaction Time Paradox and the Dual Process Theory

In the 1960s RT was introduced as a measure that could be used to test predictions about the order in which feature comparisons were made during the comparison of a test item with a memory representation in a recognition task (Sternberg, 1969). In order to eliminate errors due to encoding and retention, a very simple recognition task was used: the same-different task. A study item was followed seconds later by a test item. The task was to respond as rapidly as possible whether the test item was the *same* as the study item or *different* (Egeth, 1966; Bamber, 1969; Proctor and Healy, 1987). The task produced paradoxical results that appeared to rule out a single process comparison model of recognition. A single process model predicted that RT would decrease as a function of the number of differences between the test item and the study item. Hence, *different* responses to test items completely different from the study item would be the fastest and *same* responses to test items identical to study items would be the slowest. In fact, consistent with the single-process comparison model, RT decreased as a function of the number of differences for *different* responses. However, contrary to the single process comparison model, *same* responses were faster than *different* responses. The results were consistent with a dual process idea in which *same* responses were generated by one process and *different* responses were generated by another process.

Atkinson and Juola (1974) found the same paradoxical RT results in a conventional word recognition task, where participants had to respond as fast as possible whether a test item had appeared on a study list. A single process model predicted that RT would be a function of such factors as study-list size and study-list position for targets and that hits would be faster than correct rejections. In fact, consistent with the single-process model, hit RT was a function of list size and list position for slower responses. However, contrary to the single process comparison model, the fastest responses included both hits and correct rejections and their speed was not a function of list variables. The results were consistent with a dual process idea, that recognition involves both a rapid check for the prior occurrence of an event and an organized conceptual search process (Juola, Fisher, Wood and Atkinson 1971, Atkinson and Juola, 1973, 1974; Mandler, Pearlstone, and Koopmans, 1969; Mandler, 1979, 1980, 1991; Graf and Mandler, 1984; Graf, Squire, and Mandler, 1985; Hintzman and Curran, 1994; Jacoby and Dallas, 1981; Jacoby, 1991). The two processes of the dual process theory of recognition memory came to be called recollection and familiarity. Recollection was assumed to be a relatively slow process that consists of retrieving specific details associated with the prior presentation of an item, whereas familiarity was assumed to be a relatively fast process that allows one to appreciate the fact that the item was previously encountered even though no contextual detail can be retrieved.

2.3 The Dual Process Theory: 1975-Present

An early version of the dual process theory proposed by Atkinson and Juola (1973, 1974) was the two criterion model. According to this model, if the familiarity of a test item falls above a high criterion value or below a low criterion value, then a fast, familiarity based decision is made (old or new, respectively). If the value instead falls between the two criteria, then a search process is initiated and, if successful, leads to a slower recollection based “old” decision. Thus, the subject was thought to resort to recollection as a backup process whenever familiarity failed to provide a clear answer.

Initially, Mandler et al. (1969) also argued for a conditional search model in which recollection was only initiated if familiarity led to an ambiguous response, but in subsequent articles the model was modified so that the processes were independent and operated in parallel, but with familiarity typically being faster than recollection (Mandler, 1980).

Ironically, despite its central role in the initial consideration of the dual process hypothesis, in subsequent decades RT was abandoned as a measure and theories of recognition continued to be studies within the framework of signal detection theory. An influential paper by Tulving (1985) introduced the terminology that has been used to characterize the two processes ever since. Tulving (1985) distinguished between two states of awareness associated with the conscious experience of memory. One state, corresponding to retrieval from episodic memory, involves the awareness of a past event as being autobiographical in nature. Another state, corresponding to retrieval from semantic memory, involves the awareness of previously acquired knowledge but without any autobiographical component. Tulving (1985) proposed that participants could indicate which state of awareness applied to a particular memory by saying “remember” if it was retrieved from episodic memory or “know” if it was retrieved from semantic memory. In a typical remember/know experiment, participants are presented with a study list of words and are later presented with a longer test list and asked to identify which words were on the study list, i.e., whether each word is old or new. For each word that is declared to be old, they are further asked to indicate if they remember its appearance on the list or just know that it appeared on the list. The distinction between remembering and knowing was further developed by Gardiner (1988). According to him, the remember/know distinction maps closely onto Mandler's (1980) distinction between recognition by retrieval and recognition by familiarity, such that, remember judgments reflect recognition by retrieval, while know judgments reflect recognition by familiarity.

The dual process model of recognition was not immediately accepted. An alternative single process interpretation of remember/know judgments, was proposed by Donaldson (1996), such that, remember and know judgments simply reflect different degrees of memory strength and, therefore, different levels of confidence. According to his account, remember judgments are made to items that exceed a high memory strength criterion, whereas know judgments are made to items that only exceed a lower criterion. The lower criterion is also equivalent to the old/new decision criterion. The remember hit-rate corresponds to the proportion of the target distribution that exceeds the high criterion, and know hit-rate corresponds to the proportion of the target distribution that falls between the low and high criteria with the overall hit rate being the sum of those two values.

Donaldson's report led to several years of intensive investigative effort comparing the predictions of single process versus dual process models. Evidence accumulated in favor the of the dual process hypothesis. A double dissociation between the effects of other variables on remember versus know judgments provided evidence for two processes.

In comprehensive reviews, Yonelinas (2002) and Diana, Reder, Arndt and Park (2006) argued that the evidence decisively favored a dual process account of recognition, according to which, familiarity consists of a memory signal associated with the item itself, whereas recollection consists of the retrieval of associated source information. Thus, according to dual process models, the essential difference between the subjective experience of recollection and familiarity is the content of the memory signal.

Table 2.1 (results 1-8) summarizes evidence supporting the idea that a recollection process is involved in recognition judgments and hence recognition can only be explained within the context of a two-process model. First, low-frequency words produce more hits but fewer false alarms than high-frequency words (Glanzer and Adams, 1985). The dual process model explains the opposite effects of frequency on hit versus false alarm rates by assuming that the hit and false alarm effects are products of different processes. The hit portion of the effect is caused by the recollection process. Low frequency words are more novel than high frequency words, hence are more likely to be encoded in the study-list-context, and therefore more likely to be effective cues for recollecting the study-list during the recognition test. The higher probability of recollecting low frequency targets compared with high frequency targets results in more hits for low frequency targets than for high frequency targets. However, the false alarm portion of the effect of frequency is the result of high frequency words being more familiar than low frequency words. Hence, false alarms are more likely for familiar high frequency distractors than for unfamiliar low frequency distractors when familiarity controls the recognition judgment.

Second, in associative recognition tasks, participants study pairs of words and are tested on intact pairs as well as on rearranged pairs. The participants are required to respond old to intact pairs and new to rearranged pairs. The familiarity of the elements of both types of pairs at test should be approximately equal, because all the words have been studied previously. However, intact pairs can be discriminated from rearranged pairs in a recognition task. Discrimination between intact and rearranged pairs is assumed to require recollection (Gronlund and Ratcliff, 1989). Hence, associative recognition tasks rule out the possibility of a single process model based on familiarity.

Third, in a plurality recognition task, the distracter items are new words, as well as studied words in reversed-plurality form. The familiarity of reversed-plurality distracters should be very similar to the familiarity of the study item, thus requiring recollection of the study event to determine the exact form of the word that was seen previously. This is supported by the fact that there are more know responses to similar lures and more remember responses to target items and hence discrimination of targets from reversed-plurality distracters indicates recollection (Hintzman and Curran, 1994).

The perceived familiarity of an item is assumed to be generated by the perceptual process and recollection is assumed to be a post-perceptual process in which a representation of the item is compared with memory. So, the familiarity of a probe should be available for a recognition judgment before recollection. Hence, a dissociation in the speed at which the two types of information become available is predicted by the dual process model. The fourth result shown in Table 2.1 confirms this. When recognition judgments are made under time pressure (500-800 msec), there is no difference in hit rate for low frequency and high frequency words; but high frequency words still produce more false alarms than do low frequency words (Balota et al., 2002; Joordens and Hockley, 2000). The response deadline procedures force participants to respond by using the faster familiarity process, whereas longer response times allow the use of recollection. Also, Rotello and Heit (2000) showed that false alarms to re-paired items in an associative memory task were greater under time pressure presumably, the result of familiarity-based responses and decreased under conditions in which participants were given more time to respond.

Recollection is only possible if the target has been encoded in the study context during the study task. Dividing attention during the study task reduces the opportunity to encode study items in context. Hence, reduced recollection during the subsequent recognition test is predicted by the dual process model, as confirmed by the fifth result in Table 2.1. For example, dividing attention had larger disruptive effects on word-voice and word-location associative recognition tasks that require recollection, than on item recognition tasks for which familiarity is informative (Troyer, Winocur, Craik, and Moscovitch, 1999),

On the other hand, since familiarity is the product of the perceptual process, factors that affect perception affect familiarity without affecting recollection. So, as indicated by the sixth result in Table 2.1, priming increases perceptual fluency, which increases familiarity, but does not influence recollection. For example, briefly flashing a word just prior to presenting it in a recognition test, visually presenting a word more clearly than other words in a test, revealing a word letter by letter compared to presenting the entire word or presenting a word in a conceptually predictive compared to unrelated context, increases the familiarity of the target items, but has no effect on recollection.

Consistent with this claim, fluency effects are more readily observed in item than associative recognition tests under normal study conditions, but are observed for both item and associative recognition tests when study time is extremely brief, thus limiting the encoding of information that would support recall or recollection (Cameron and Hockley, 2000; Westerman, 2001).

Seventh, changing the perceptual characteristics of words between study and test reduces perceptual fluency, hence reduces familiarity, but does not influence recollection. Changing modality had larger effects on speeded compared with non-speeded test conditions (Toth, 1996), suggesting that the manipulation has larger effects on familiarity than recollection.

Finally, the effect of the study task on the familiarity of the target decreases over intermediate retention intervals of 10-20 seconds, which is the eighth result shown in Table 2.1. Across 32 intervening items in a continuous recognition test, recognition memory for single items decreased significantly, whereas memory for associative recognition remained unchanged (Hockley, 1991, 1992), suggesting that familiarity, but not recollection, decreased across these delays. A similar pattern of disproportional forgetting for item recognition compared to associative recognition was also seen in procedures in which a study list is followed by a separate test list (Hockley, 1991, 1992).

Diana et al. (2006) therefore suggested that models of recognition memory must include a recollection process, in addition to familiarity, in order to explain the different effects of the variables presumed to affect familiarity versus recollection on responses presumed to be based on familiarity versus recollection in recognition memory.

2.4 Segregated versus Integrated Dual Process Models

The determination that recollection and familiarity both influence recognition raises the question of how these two kinds of information are combined. As shown in Table 2.1, one possibility is that the two kinds of information are **segregated** when a recognition judgment is made. Recollection and familiarity are tabulated separately for a probe and if either exceeds its criterion a recognition judgment is made. The other possibility is that the two kinds of information are **integrated** when a recognition judgment is made. Recollection and familiarity are combined and if the total combined information exceeds a criterion a recognition judgment is made. These two classes of models, namely, segregated models and integrated models, are both compatible with the dual process theory of recognition. However, they make conflicting assumptions about the functional nature of the underlying processes or systems, which lead to divergent predictions.

The foundational assumption of the segregated models is that the processes tabulating recollection and familiarity operate independently during retrieval. So a recognition decision is based either on recollection or on familiarity. This either/or character of segregated models derives from the assumption that recollection is essentially a categorical threshold phenomenon, and a test item either occasions conscious recollection of its prior occurrence on the list or it does not in an all or none fashion. When it does, it yields high confidence that the item is old (Yonelinas, 2002). Familiarity on the other hand is assumed to be a continuous variable, and because both targets and distracters have some degree of familiarity associated with them, these decisions are thought to be characterized by the signal detection process. Hence, recollection is assumed to yield only high confidence old decisions, whereas only familiarity plays a role in decisions made with lower degrees of confidence.

Integrated models on the other hand assume that recollection, like familiarity is a continuous process that is associated with low, medium, or high degrees of confidence, depending on the degree of recollection that is occasioned by the test item. Unless data provided by the two processes were perfectly correlated, the information provided by the two processes would result in more accurate recognition when combined than either one would alone. Therefore, in integrated models, recollection and familiarity are combined and equally weighted when making recognition judgments. Individual recognition memory decisions are therefore not process pure. Instead, both processes (recollection and familiarity) play a role in decisions about particular test items even when those decisions are made with lower levels of confidence.

Hence, an important issue of disagreement between the two classes of models is whether recollection is better characterized as a dichotomous process (segregated models) or as a continuous signal detection process (integrated models). The accumulation of results has established that recollection is a continuous variable, like familiarity. Several of these results are from source memory tasks, where participants are typically first asked for an old/new decision and then asked to indicate the item's source. Identifying the target item's source entails recollection of source information.

The ninth result shown in Table 2.1 is that partial recall of a study item is possible, so that recollection is at least a graded, if not continuous, variable. Several different experiments have demonstrated this. Dodson, Holland, and Shimamura (1998), presented words on a study list in two different male voices and two different female voices and found that participants often remembered partial detail about the source (e.g., that the word was spoken in a female voice) even when the specific source (Female 1 or

Female 2) could not be remembered. Simons, Dodson, Bell, and Schacter (2004) reported the same phenomenon. Hence, recollection of source information occurred in a graded fashion.

The findings of Dodson et al. (1998) suggest that recollection of source information occurs in degrees, and hence provide evidence that recollection is best described as a continuous variable. Kurilla and Westerman, (2010) examined whether people can partially recollect source information about stimuli that they fail to identify. In two experiments, participants exhibited reliable source memory for fragmented versions of previously studied words even when they could not come up with the correct solution to the fragments, and hence labeled them as unidentified. Hence, partial recollection occurred for both identified and unidentified stimuli and when it did, it yielded fairly low levels of confidence, especially in the case of unidentified stimuli.

In fact, it has been shown that recollection is characterized by a positive correlation between confidence and accuracy, which is the tenth result in Table 2.1. Mickes, Wais, and Wixted (2009) demonstrated this by using a source memory procedure, where some items on a list were associated with one source attribute (e.g., the color red), and others are associated with a different source attribute (e.g., the color blue). On a later recognition test, participants were presented with test items in a source-neutral fashion (e.g., in black) and asked to recollect the original source attribute. Participants were also asked to rate their confidence in the item’s source. Confidence and accuracy were positively correlated. Wixted and Stretch (2004) further demonstrated that there is a strong correlation between remember hit rate and remember false alarm rate across participants, indicating that recollection is a continuously distributed variable, so that a criterion is needed to decide whether enough recollective detail has been retrieved to warrant a remember response, which is contrary to the central assumption of the segregated models that recollection is a threshold process

These results seem inconsistent with the way in which recollection operates in segregated models, according to which recollected information always leads to high confidence recognition responses. Rather, they offer support for the assumption of integrated models that recollection is a continuous process characterized by a positive correlation between confidence and accuracy.

The process purity assumption of segregated models as it applies to a decision about an individual test item means that if the item is recognized as being old, the assumption made by the model is that the participant either recollected the item in sufficient detail to warrant a high confidence old decision (in which case its degree of familiarity was irrelevant) or did not recollect the item and utilized the familiarity process instead (in which case recollection played no role). So, in the context of remember/know judgments, a remember response is made when recollection occurs. A know response is supplied when the decision is based exclusively on familiarity.

This assumption of segregated models has been brought into question by the eleventh result shown in Table 2.1, that know judgments entail measurable degrees of recollection (Eldridge, Engel, Zeineh, Bookheimer, and Knowlton, 2005; Hicks, Marsh, and Ritschel, 2002; Wais, Mickes, and Wixted, 2008) For example, Eldridge et al. (2005) and Hicks et al. (2002) showed that subjects often make accurate source judgments (which depend on recollection) for items that receive a know response. Wais et al. (2008) found that source recollection was greater for remember judgments than for know judgments, but they also found that recollection was above chance for items judged to be known (even when participants were asked to make a source recollection decision before making remember/know judgment). Of course it is possible for there to be partial source recollection that is not used in the know judgment. This would be the case if there was not enough source information to exceed the recollection threshold. However, Wais et al. (2008) found that high confidence source judgments were followed by a high confidence know response. If they were high confidence partial recollections, they should have exceeded the recollection threshold. Hence, know responses involved less recollective detail than remember responses but they did not signal the absence of recollective detail.

Integrated models by definition account for the influence of recollected information on know judgments, since they assume that recollection and familiarity are combined in order to make a recognition judgment. Hence, consistent with the empirical evidence, these models do not view remember and know judgments as strictly mapping onto recollection and familiarity respectively, but rather as involving different degrees of both recollection and familiarity. So, a remember judgment may involve a higher degree of recollection (and lower degree of familiarity), while a know judgment may involve a lower degree of recollection (and higher degree of familiarity).

As shown in Table 2.1, results are consistent with integration rather than segregation of the two processes in the recognition judgment. Furthermore, there are other results that the extant segregated models fail to predict when their specific assumptions are considered. The next section considers the fit of the segregated models to the recognition data in more detail before moving on to the integrated models in the subsequent section.

2.5 Segregated Models

Within the category of segregated models, two kinds of models are possible. One possibility is that the two kinds of information are processed in parallel, and the other is that the two kinds of information are processed serially. Mandler (1980) proposed a model where the recollection and familiarity processes were independent and operated in parallel, but with familiarity typically being faster than recollection. If people can make a post-recognition judgment about the basis of the recognition judgment, then it should therefore be the case then that know hits should be faster than remember hits. Furthermore, since familiarity is available faster than recollection and both processes operate in parallel, the model essentially predicts that recollection-based remember judgments can only be made if familiarity-based know judgments are not available. This again implies that know hits should be faster than remember hits. However, Dewhurst and Conway (1994) found that old decisions that were followed by a remember response were faster (by 500–700 msecs) than those followed by a know response. This pattern has been replicated in all the studies that have analyzed reaction times (Dewhurst, Holmes, Brandt, and Dean, 2006; Wixted and Stretch, 2004). Hence, as seen in Table 2.1, the model is contradicted by the twelfth finding that hits called remember judgments are faster than hits called know judgments. Furthermore, the model does not make any specific prediction regarding the relationship between remember/know judgments and average confidence ratings. However, as indicated in Table 2.1 (result 13) remember responses to targets (remember hits) are made with higher confidence than are know hits. This was first demonstrated by Tulving (1985), and replicated in several other studies (Stretch and Wixted, 1998; Dobbins, Kroll and Liu, 1998; Heathcote, Freeman, Etherington, Tonkin and Bora, 2009) where subjects were first asked to make an old/new judgment and for any item that received an old decision, the subjects were then asked to make a remember/know judgment followed by a confidence rating. In every case, the average confidence in remember hits significantly exceeded the average confidence in know hits, a result not accounted for by Mandler's model.

The other possibility for segregated models is that the two kinds of information are considered serially. Atkinson and Juola (1974) proposed a segregated serial model in which if familiarity either exceeds a high criteria or falls below a low criterion, a know-old or a know-new response is made, respectively. Otherwise, a recollection judgment is made. As shown in Table 2.1, the twelfth result, remember hits are faster than know hits, is inconsistent with these assumptions. The model also does not make any predictions about the relationship between remember/know judgments and average confidence ratings.

The Atkinson Juola (1974) and Mandler (1980) models are based on empirical findings which demonstrate that familiarity is **available** faster than recollection (Table 2.1, result 4). However, contrary to this finding, remember/know studies also established that remember responses are generally faster than know responses (Table 2.1, result 12), a result that could not be accounted for by either model. The segregated dual-process models that followed therefore made assumptions that could account for both findings and hence make the model consistent with the fact that even though familiarity is available before recollection, remember judgments (which are based on recollection) are faster than know judgments (which are based on familiarity).

A more recent segregated dual-process model is the hybrid model proposed by Yonelinas and colleagues (Yonelinas, 1994, 1997, 1999, 2001a, 2001b; Yonelinas, Kroll, Dobbins, Lazzara, and Knight, 1998; Yonelinas, Kroll, Dobbins, and Soltani, 1999), and subsequently refined by Parks and Yonelinas (2007), according to which if a target item on a recognition test occasions recollection, then a high confidence old decision is made; if recollection fails, however, then a familiarity-based decision is made. Thus, in this model, the participant is thought to resort to familiarity as a backup process whenever recollection fails to occur. Since the model assumes that remember/know judgments are process pure, it therefore correctly predicts the thirteenth result in Table 2.1, that remember responses to target*s* are made with higher confidence than are know responses. Furthermore, since the model assumes that when a target item is encountered on a recognition test the subjects attempt recollection first and if recollection fails then a familiarity based know decision is made, it correctly predicts that remember hits are faster that know hits (Table 2.1, result 12). Hence, know responses are slow because they are made only if remembering fails.

Notice that partial recollection is shown as contradicting the Atkinson and Juola (1974) and Mandler (1980) but not the Yonelinas (1994) model in Table 2.1 (result 9). The first two segregated models treat recollection as an all-or-none process. However, Parks and Yonelinas (2007) stated that the Yonelinas (1994) has been misunderstood, and that all-or-none high threshold for the recollection process does not mean that either all of the information about a study event is recollected or none of the information is recollected; rather, threshold refers to the fact that an item will only be recognized if its memory strength exceeds a specific threshold; items falling above the threshold are recognized and those falling below the threshold are not.

Hence, the model allows for the possibility that one can recollect a little or a lot about a prior episode; so within the model recollection is a continuous process. This however, does not affect how Yonelinas' model describes the relationship between recollection and confidence. The model assumes that no matter what the degree of recollection, if it exceeds the threshold, it will result in a high confidence old decision. Hence, any degree of recollection always yields high confidence. However, as shown in Table 2.1 (result 10), this means that the model does not predict the observed correlation between confidence and accuracy for recollection-based recognition judgments.

If recollection fails to occur for a particular item, a response is based on familiarity instead. If the familiarity of the test item exceeds a criterion level, it occasions a know judgment; otherwise, the item is declared to be new. When recollection does occur, it is not always accurate. Yonelinas (2002) suggested that under conditions in which study lists contain a number of highly associated items, subjects could falsely recollect distracter items that were associated with the studied items. Hence, a distracter similar to a target could potentially cue a recollection, implying that remember false-alarms could reflect false recollections. As mentioned in the previous section, Wixted and Stretch (2004) demonstrated that there is a strong correlation between remember hit rate and remember false alarm rate across participants. So, participants who have a high remember hit rate also have a high remember false alarm rate. Hence, if it is assumed that remember false alarms reflect false recollection, it must also be assumed that recollection is a continuous process and that participants use a criterion for deciding when to make a remember judgment.

Based on the post-hoc suggestions offered by Yonelinas (2002) and Parks and Yonelinas (2007), it seems like Yonelinas's model departs from its high threshold assumption and shifts towards a continuous variable description of recollection. Furthermore, recall that the model assumes that when an item exceeds the recollection criterion a fast, confident remember hit is made and when an item fails to exceed the recollection criterion a slow, less confident know judgment is made. Consequently, remember hits are predicted to be faster and more confident than know judgments. However, since in such a continuous criterion based model, remember false alarms are also the result of an item exceeding the recollection criterion, remember hits are also predicted to be faster and more confident than know judgments. The model therefore predicts that remember false alarms will on average be made with greater confidence and higher speed than know hits and false alarms.

As indicated in Table 2.1 (result 14-17), these predictions are consistent with empirical results. Stretch and Wixted (1998) conducted four experiments in which subjects were first asked to make an old/new judgment and to do so as quickly as they could without sacrificing accuracy. For any item that received an old decision, the subjects were then asked to make a remember/know judgment. Finally, all the items were given a confidence rating. In every case, the average confidence in remember false-alarms significantly exceeded the average confidence in know hits and know false-alarms. Dobbins et al. (1998) conducted a two picture recognition task in which similarity between targets and distracters was varied systematically by comparing performance for choices between studied and unstudied halves of the same scene versus different scenes. The average confidence in remember false-alarms significantly exceeded the average confidence in know hits and know false alarms, which are the fourteenth and fifteenth results in Table 2.1. These results were also replicated by Heathcote et al. (2010).

Furthermore, Wixted and Stretch (2004) reported that not only are remember false alarms faster than know false alarms but remember false alarms are also faster than know hits, which are the sixteenth and seventeenth results in Table 2.1. This compelling pattern has been observed in numerous studies since that time (Dewhurst, Holmes, Brandt, and Dean, 2006; Duarte, Henson, and Graham, 2008; Wheeler and Buckner, 2004; Wiesmann and Ishai, 2008). In all of these studies, subjects were asked for old/new decisions followed by remember/know judgments and reaction times were measured for the old/new decision. The reaction times associated with incorrect remember judgments were faster than those associated with both correct and incorrect know judgments. Hence, predictions of Yonelinas's (2002) elaborated model that remember judgments, whether hits or false alarms, are faster and more confident than know hits, are in agreement with empirical data (as indicated in Table 2.1).

Nevertheless, these post-hoc elaborations have not been incorporated in the original mathematical model proposed by Yonelinas, Dobbins, Szymanski, Dhaliwal and King (1996). The probability of incorrectly accepting a new item is equal to the probability that its familiarity exceeds the response criterion: P(‘‘old’’| new) = ($F_n > c$). As per this equation, false alarms should always be know judgments and never remember judgments. Hence, there are considerable inconsistencies in the verbal and mathematical description of the model. Despite verbal explanations to account for empirical results, mathematically the model does **not** account for remember false alarms and any related predictions (Table 2.1, result 14-17).

2.6 Integrated Models

A variety of models assume that a recognition response is made after familiarity and recollection information are integrated.

2.6.1 Single-Decision-Process Model

Kelley and Wixted (2001) and Wixted and Stretch (2004) proposed an integrated model based purely on signal detection theory, as shown in Figure 2.3, in which recollection and familiarity information are combined for a recognition decision. The model is functionally equivalent to Donaldson's single-information-source model but makes the additional assumption that two kinds of information, recollection and familiarity, are

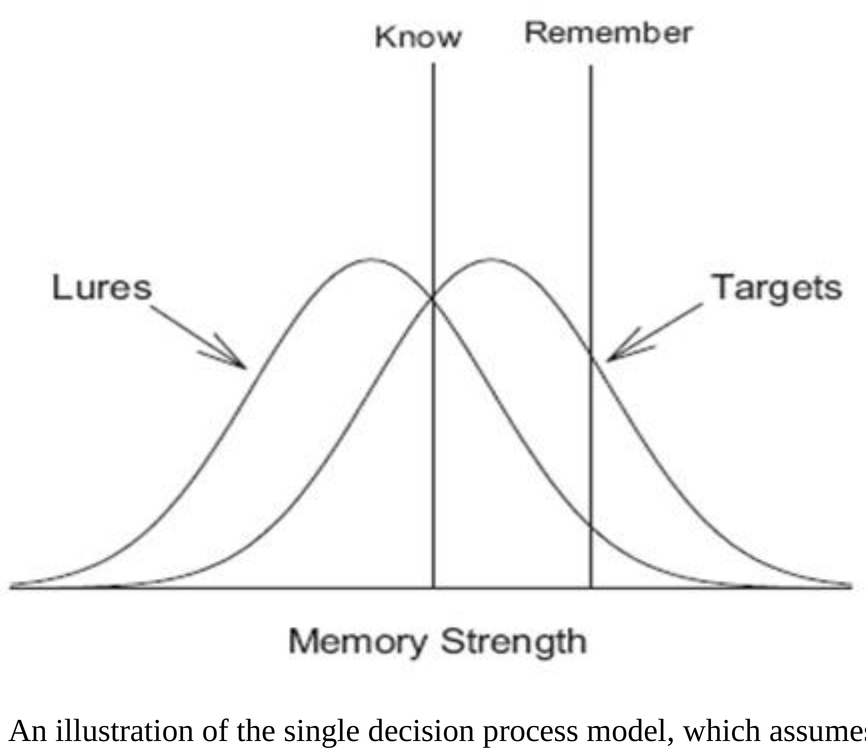

Figure 2.3. An illustration of the single decision process model, which assumes that recollection and familiarity are combined for a recognition decision and remember/know judgments reflect memory strength.

collected in order to account for the effect of recollected information on know judgments. Since the model views recollection as a continuous process, it correctly predicts that recollection confidence and accuracy will be correlated, as indicated in Table 2.1 (result 10).

The single-decision-process model assumes that individual recognition memory decisions are not process pure. Instead, both processes (recollection and familiarity) play a role in the decision about a test item. In order to make an old/new decision, subjects sum familiarity and recollection signal strength and then use that summed value to decide whether or not the item appeared on the list. Items for which this combined strength of memory signal exceeds a certain old/new decision criteria are judged as old.

For a remember/know task, the subject’s job is to indicate the basis for the old/new decision that was just made. The model assumes that subjects set two decision criteria along the strength-of-memory axis, a higher remember criteria and a lower know criteria, and respond accordingly. A remember judgment is made when the strength of the memory signal exceeds the high criterion, which exceeds the minimal criterion for responding old. By contrast, a know judgment is made when the strength of the memory signal only exceeds the lower criterion for responding old but does not exceed the higher criterion for a remember judgment. In this case, the signal is strong enough for the item to be declared old, but it is not strong enough to declare that it is remembered, so it is declared to be known instead. Items that fall below the lower criterion are declared to be new.

Most items that exceed the high remember criterion would be associated with considerable recollection. That is, in most cases, one reason why the item is high enough in strength to exceed the remember criterion is that the recollective component is strong. However, because the model rejects the process pure view of remember/know judgments, it is possible for some items to fall above the remember criterion mainly on the basis of one or the other process. Thus, a remember response denotes items that are high in strength because either the recollective component or the familiarity component (or both) is high in strength. Similarly, items that receive a know response are not process pure either, because the associated memories are not devoid of recollective detail. Instead, a know response denotes an item that is low in strength because neither the recollective component nor the familiarity component is strong. Even so, some recollective detail may be present.

The old/new decision criterion is placed at the point of maximal subjective uncertainty. From the participant’s point of view, an item with memory strength that falls exactly at the old/new criterion is as likely to be a target as it is to be a distracter. The reaction time rule derived from this model holds that the speed of a recognition decision is inversely related to confidence i.e., as confidence increases, reaction times decrease. Hence, the model assumes that there is an inverse relation between confidence and reaction time. Because the memory strengths of items associated with know judgments are closer to the old/new criterion than the memory strengths of items associated with remember judgments, know judgments are made more slowly than remember judgments. The model therefore correctly predicts that remember hits are on average made faster than know hits (Table 2.1, result 12). Furthermore, since subjects set a higher remember criteria and a lower know criteria along the memory strength axis, remember responses to targets are made with higher confidence than are know responses (Table 2.1, result 13).

Furthermore, according to the model, remember false-alarms are made to distracters with a strength that happens to exceed the high remember criterion on the memory strength axis. The model therefore predicts that remember false alarms will on average be made with greater confidence than know hits and false alarms. Since the memory strengths of distracters that receive incorrect remember judgments (remember false alarms) are higher on the memory strength scale than targets that receive correct know judgments (know hits), the model also predicts that remember false alarms will be made faster than know hits and know false alarms. Hence, the predictions of the single-decision-process regarding false alarms are in agreement with empirical data as indicated in Table 2.1 (result 14-17).

However, the single-decision-process model is not without its problems. In particular, the model implies that the most confident recognition judgments will be called remember judgments. However, the eighteenth result shown in Table 2.1 is that this is not always the case. Suppose for a particular participant, the remember criterion is placed between the criteria for making confidence ratings of 5 or 6, and the know criterion is placed between the criteria for making confidence ratings of 3 or 4. A participant whose decision criteria are arranged in this manner should provide confidence ratings of 4 or less for know judgments and provide confidence ratings of 5 and above for remember judgments. This implies that, no know judgment would receive a confidence rating of 6, and no remember judgment would receive a confidence rating of 4. In practice however, remember and know judgments from an individual participant often show much more variability in confidence ratings, which is shown as the nineteenth result in Table 2.1. That is, a participant's remember judgments might consist mainly of confidence ratings of 6, but they may include some confidence ratings of 5, and a few confidence ratings of 4 may be evident as well. Most know judgments might consist mainly of confidence ratings of 4 and 5, but some confidence ratings of 6 may be observed as well.

For the single-decision-process model, the only way to explain this is to assume that either the confidence criteria or the remember criterion (or both) exhibit item to item variability with respect to each other. That is, for one test item, the criteria might be placed as described in the above mentioned example. For another test item, either the confidence criteria or the remember criteria (or both) may shift such that the remember criterion falls above the criterion for making a confidence rating of 6. This kind of instability in the placement of the criteria can allow remember/know judgments to share more than one confidence rating. However, it has not been shown that the placement of criteria is, in fact, so variable.

The model attributes participants no capacity to accurately indicate which process mainly informed their recognition decision. So, if the criterion remain fixed, an item with high recollection strength and low familiarity strength might lead to a remember response, but another item with high familiarity strength and low recollection strength could produce exactly the same remember response. Hence, according to the single-decision-process model, remember/know judgments can not be used to distinguish between decisions that are mainly based on recollection and those that are mainly based on familiarity.

In contradiction to this prediction, Wixted and Mickes (2010) reported experimental data demonstrating that a memory trace associated with a high confidence know judgment is different from a memory trace associated with a high confidence remember judgment in that the former is primarily based on familiarity, whereas the latter involves a high degree of recollection. Participants studied a list of targets, half in red or blue (color source) and half on the top or bottom of the screen (location source). On the subsequent recognition test, the targets were randomly intermixed with distracters and, for each test item, participants rated old/new confidence. For words judged to be old, participants were first asked to make a remember/know/guess judgment and were then asked to recollect source details. When the highest confidence ratings for remember and know judgments were examined separately, the old/new accuracy was approximately 91% in both cases, but source accuracy which is an objective measure of recollection, was significantly greater for the high confidence remember judgments (80% correct) than for the high confidence know judgments (66% correct), shown as the twentieth result in Table 2.1.

Hence, remember/know judgments, though not process pure, do distinguish between decisions that are mainly based on recollection and those that are mainly based on familiarity. In particular the high-confidence know-judgments have a lower level of source accuracy despite having the high level of old/new accuracy as high-confidence remember-judgments. These results do not support the assumption of the single-decision-process model that remember/know judgments simply represent different degrees of combined memory strength.

To account for these findings, the integrated recognition model has been elaborated into an integrated-recognition, segregated post-recognition model by Rotello et al. (2004) and Wixted and Mickes (2010). In these models, recognition is a fast process involving the integration of recollection and familiarity. However, people also have the ability to engage in reflective processes and make remember judgments, which rely on segregated recollection, and know judgments, which rely on segregated familiarity.

2.6.2 Sum-Difference Theory of Remembering and Knowing (STREAK)

Rotello et al. (2004) proposed that memories vary along two dimensions, global and specific strength, which are somewhat analogous to familiarity and recollection. In their two dimensional model (STREAK), one dimension represents global familiarity, and another orthogonal dimension represents recollection of specific details associated with the item. STREAK assumes that specific and global forms of evidence contribute in different ways to confidence versus remember/know decisions; namely, increasing specific strength promotes higher confidence ratings and more remember responses whereas increasing global strength promotes higher confidence ratings and fewer remember (hence, presumably more know) responses.

To make an old/new decision, subjects sum the two components (recollection and familiarity) of strength and then declare the item to be old if that sum exceeds a decision criterion. This is exactly like the assumption of the single-decision-process model that subjects sum familiarity and recollective strength and then use that summed value to decide whether or not the item appeared on the list (Kelley and Wixted, 2001).

However, STREAK also assumes that subjects compute the difference between the specific and the global strengths of the test item when trying to decide whether the item was remembered or known. If that difference exceeds a criterion, subjects declare the item to have been remembered; otherwise, it is declared to be known. Hence, in contrast to single-decision-process model, which assumes that subjects set two decision criteria (confidence criteria and remember/know criteria) along the strength of memory axis, this model assumes that subjects base their remember/know and confidence (old/new) judgments on different kinds of information. This assumption implies that in a remember/know task people can report qualitatively distinct memory experiences.

Furthermore, the model does not predict any particular relationship between average confidence ratings and remember/know judgments. This allows for extensive overlap between remember/know judgments and confidence ratings and hence also accounts for high confidence know judgments. Hence, the model allows for the possibility of high confidence know judgments and overlapping confidence ratings for remember and know judgments, shown as the eighteenth and ninteenth results in Table 2.1.

However, since the model does not predict a relationship between confidence ratings and remember/know judgments, it fails to predict the thirteenth result shown in Table 2.1, that remember judgments are made with higher confidence than know judgments. Furthermore, it does not offer any predictions regarding the relationship between remember/know false alarms, reaction times and confidence ratings. The strong relationship between confidence ratings, reaction times and remember/know judgments (for example, remember judgments are invariably associated with higher average confidence than are know judgments) therefore makes the model hard to reconcile with empirical evidence (Table 2.1, result 13-17). Furthermore, Dougal and Rotello (2007) and Starns and Ratcliff (2008) demonstrated that STREAK does not provides a good fit to remember/know data.

2.6.3 Continuous Dual Process (CDP) Model

Wixted and Mickes (2010) have recently proposed an extension to their single-decision-process model, as shown in Figure 2.4, adding recollection as an additional orthogonal process, based upon a continuous signal detection scale. So, a single, integrated recognition process is followed by a segregated remember/know judgment, just as in Rotello et al.'s (2004) STREAK. An old/new recognition decision is assumed to be based

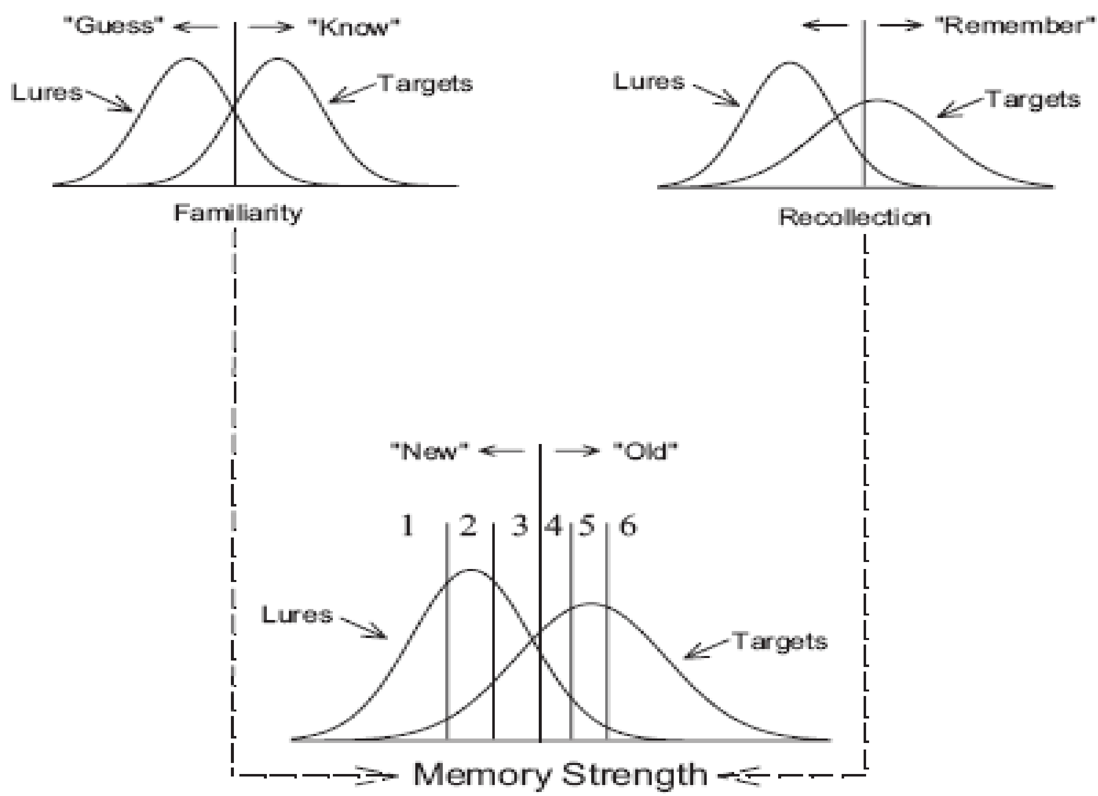

Figure 2.4. An illustration of the continuous dual process model. For old/new decisions the recollection and familiarity signals are assumed to be summed. If the participant is asked to make a remember/know/guess judgment, memory is then queried for recollection, and the participant makes a remember judgment if the recollection signal exceeds a decision criterion. If recollection fails to exceed that criterion, memory is queried for familiarity, and the participant makes a know judgment if familiarity exceeds a criterion.

on the sum of the recollection and familiarity signals for a particular test item. That is, the memory strength signal for a test item consists of recollection and familiarity combined. The confidence criteria are placed along the aggregated memory strength axis. This means it makes the same predictions as the single-decision-process model described above. So, as shown in Table 2.1 (result 13 - 17), like the other single-decision-process models, this model predicts that on average remember judgments will be associated with higher confidence, higher accuracy, and faster old/new reaction times than know judgments. However, remember and know judgments are based on different kinds of data, recollection and familiarity, respectively, represented in the model as different dimensions of memory strength. The remember criterion is placed on the recollection axis, and the know criterion is placed on the familiarity axis.

The model therefore assumes that remember judgments are based on a recollection dimension and that know judgments are based on a familiarity dimension. So, an old response associated with a high confidence know judgment is different from an old response associated with a high confidence remember judgment. When memory is queried by asking whether the test item is old or new, the memory strength variable is assumed to consist of the combination of recollection and familiarity.

When the participant is next asked to make a remember/know judgment, the memory strength variable is determined by two separate queries of memory. A remember judgment is made if the strength of the recollection signal exceeds the remember criterion. If the degree of recollection fails to exceed the remember criterion, then the participant makes a know judgment (if the only options are remember and know) or interrogates the familiarity dimension (if the options are remember, know or guess). If the degree of familiarity exceeds the know criterion, a know judgment is made; otherwise, a guess judgment is made. Hence, a know judgment in this model implies that the amount of familiarity associated with the test item exceeds a criterion on the familiarity dimension, but it does not imply the absence of recollection. Instead, the amount of recollection is such that it simply failed to exceed the criterion on the recollection dimension. This means that the model accounts for instances where the summative signal is high, but the recollection signal alone is low, or at least not high enough to pass the remember criterion. These instances result in high confidence know responses (Table 2.1, result 18).

However, since the model assumes that the recollection axis is queried first, for a high confidence "old" decision, if the strength of the recollection signal exceeds the remember criterion, it will always be called a remember judgment, even though it may be the case that the familiarity signal is equally strong. This implies that there will always be a higher proportion of high confidence hits that will be called remember responses.

Importantly, the model allows for the possibility that individuals can report valid information about whether or not their decision was primarily based on recollection or familiarity using remember/know judgments, even though remember/know judgments do not always disentangle recollection and familiarity, which is the twentieth and final result listed in Table 2.1.

Though the CDP model can explain most of the extant findings, it has limitations. First, it does not directly predict RT results other than the relationship between confidence and RT found within the signal detection paradigm. It therefore predicts that when equated for confidence, remember and know responses should have approximately same RTs. However, as indicated in Table 2.1 (result 11-17), remember responses are on average faster than know responses. Hence, attempts to adapt it in a piecemeal manner to predict RT lead to a paradoxical conclusion. Second, the CDP is not grounded in any well established neural systems of learning and memory. Hence, it is open to the criticism that it is simply a post hoc mathematical construct with a sufficient number of parameters to account for variability in the extant data and is unrelated to any actual brain mechanisms producing recognition.

3. fMRI Activation during a Same-Different Task: Evidence for the Continuous Dual Process Accumulation Model

A dual process model of recognition implies that two distinct areas of brain activity should be found to be associated with the two different processes assumed to contribute to recognition, recollection and familiarity. A preliminary goal of many imaging investigations has been to determine whether old/new decisions that are based on recollection are associated with a different level of medial temporal lobe activity from those that are based on familiarity. The studies often rely on post-recognition remember/know judgments for this purpose

3.1 Neural Correlates of Recollection and Familiarity

Studies have consistently found that hippocampal activity is elevated for Remember judgments but not for Know judgments (Eldridge, Knowlton, Furmanski, Bookheimer, and Engel, 2000; Yonelinas, Otten, Shaw and Rugg, 2005).What does this finding suggest about the role of the hippocampus in recollection and familiarity? The answer depends on the specific cognitive model that is used to understand the meaning of remember/know judgments and therefore the brain activity associated with them.

According to Yonelinas' hybrid model, recollection is a discontinuous threshold process that either occurs for a test item or does not occur. If it does occur, the participant makes both a recollection-based old decision and a remember judgment. If it does not occur, and if the test item seems sufficiently familiar, the participant makes both a familiarity-based old decision and a know judgment. Thus, according to this account, remember and know judgments accurately distinguish between recollection based and familiarity based recognition decisions. If so, then the fact that hippocampal activity is selectively elevated for remember judgments provides evidence that the hippocampus selectively supports recollection. However, if the assumptions of Yonelinas' hybrid model are not correct, then the meaning of the measured brain activity would change.

Next consider what the same neuroimaging results would mean according to a different dual process model. Unlike Yonelinas' hybrid model, Wixted's CDP model holds that recollection (like familiarity) is a continuous signal detection process, not a discontinuous threshold process. In addition, because both processes are continuous variables that can range from weak to strong and because both provide valid evidence of prior occurrence, the CDP model assumes that recognition decisions are ordinarily based on a combined memory signal consisting of both recollection and familiarity (not on one process or the other, as is the case in Yonelinas' hybrid model).

So, if recollection and familiarity both happen to be weak for a particular test item, yet, when combined, the two processes are strong enough for the item to be declared as old, should the participant say remember or know? Wixted's CDP model assumes that participants say remember when recollection is strong (whether familiarity is weak or strong) and say know when recollection is weak (again, whether familiarity is weak or strong). If so, then remember judgments would, on average, be based on a stronger memory signal and should therefore be associated with higher confidence and higher accuracy than know judgments. Thus, the fact that hippocampal activity is selectively elevated for remember judgments could simply mean that the memory signal, whether based on recollection or on familiarity, needs to be strong in order to be detected in the hippocampus using fMRI (Squire, Wixted and Clark, 2007). Consistent with this idea, Smith, Wixted and Squire (2011) found that when steps are taken to equate confidence and accuracy for remember and know judgments i.e., when recollection and familiarity are similarly strong, hippocampal activity is similarly elevated for both.

Depending on which model is judged to be correct, the interpretation of the same activity measured in the hippocampus changes. These studies therefore do not shed light on cognitive theories but instead depend on cognitive theories to interpret the data, an interpretation that is only as valid as the cognitive theory on which it is based.

3.2 Dual-System Hypothesis of Memory

Packard and McGaugh (1996) found compelling evidence for dual systems of learning and memory in the brain. Using a maze learning paradigm, they found that after one week of training, a rat’s response in a T-maze depended on the hippocampus, but after two weeks of training, the rat’s response depended on the striatum. Research that followed in animal studies over the next two decades, has made it increasingly evident that the mammalian brain contains two integrated but distinct systems of learning and memory, (1) the instrumental system, which includes the hippocampus and recognizes perceptual patterns, and (2) the habit system, which includes the caudate nucleus of the striatum and, serially generates features of a pattern. The two systems are assumed by the dual-system hypothesis to solve the same task differently. Yin and Knowlton (2006) showed that a variety of behavioral findings in fact had a clear neural basis within the context of the two-system description of mammalian memory. Furthermore, they showed that the habit system (which includes the caudate) extended into the dorsolateral and ventrolateral prefrontal cortex.

While the dual-system hypothesis has been investigated in the context of navigational tasks for both animals and humans, it seems likely that the hippocampus and caudate perform complimentary roles in a variety of cognitive tasks. In fact, the dual-system hypothesis seems completely compatible with the dual process theory of recognition, in which familiarity is a kind of perceptual judgment that is associated with the instrumental system and the hippocampus, whereas recollection is based on the serial retrieval of details of the study episode, which is associated with the habit system and the caudate. However, despite its relevance, this work has not been mentioned in studies of human recognition

3.3 Neuroimaging Study Involving the Same-Different Task: Extending the Dual-System Hypothesis of Memory to Recognition

As we saw earlier (Section 3.1), a major weakness of the existing dual process models of recognition is that they are not related to any neural learning systems known to exist in the brain. This lacuna can filled by the dual-system hypothesis of memory developed by Packard and McGaugh (1996) (described in Section 3.2). Recollection requires a procedural component for generating the source information while familiarity is assumed to be a purely declarative representation accessed through perception. Hence, within the framework of the dual-system hypothesis, the instrumental system (which includes the hippocampus), generates a familiarity judgment based on how recently the test item has been previously perceived, and the habit system (which includes the striatum), compares the test item with a memory representation to generate a match or mismatch. As per the dual-system hypothesis therefore, the brain’s neural recognition mechanism is distributed among a variety of brain structures acting in complementary, cooperative ways.

This prediction was tested by having subjects perform the same-different matching task (Proctor and Healy, 1987), while being scanned in an fMRI scanner. In this task, subjects had to judge pairs of four letter strings as being either "same" or "different". The two strings were presented in quick succession, and participants had to respond as rapidly as possible whether they were the *same* or *different*. The two strings that formed a *same* pair were identical (i.e., the strings contained the same letters in the same order), whereas the strings that formed a *different* pair had the same letters, but in different orders.

The Proctor and Healy (1987) data revealed that the speed of *different* judgments was a function of two factors, the left-to-right position of the first letter difference between the study and test string (left matching sequence) and the sum of the distances between the position of each letter in the test string and its original position in the study string (displacement). Table 3.1 shows all possible permutations of ABCD, hence all possible different test strings when the study string is ABCD. The test strings are listed in the table in order of the length of the substring from the left matching the study string. On the first row, there is a test string with matching letters in the two left positions (left matching sequence of 2), on the next four rows there are test strings with a matching letter in the leftmost position (left matching sequence of 1), and on the remaining rows the letter of the string in the leftmost position mismatches the study string (left matching sequence of 0). The correlation between the length of the left matching sequence (2, 1 or 0 letters) and different response time (RT) was .92, $F(1,21) = 113$, $p < .001$.

Table 3.1. *All possible permutations for four letter strings used in the experiment, corresponding left matching sequence and number of pairs of each permutation type presented. Reaction time results for different responses.*

Permutation	Left matching sequence	Displacement	Number of string pairs presented	RT (milliseconds)
ABDC	2	2	24	1170
ACBD	1	4	6	1086
ACDB	1	4	6	1026
ADBC	1	4	6	1098
ADCB	1	4	6	1020
BACD	0	2	2	992
BADC	0	4	2	825
BCAD	0	4	2	912
CABD	0	4	2	862
CBAD	0	4	2	978
BCDA	0	6	2	880
BDAC	0	6	2	905
BDCA	0	6	2	877
CADB	0	6	2	976
DABC	0	6	2	847
CBDA	0	6	2	938
DACB	0	6	2	803
DBAC	0	6	2	894
DBCA	0	6	2	927
CDAB	0	8	2	878
CDBA	0	8	2	825
DCAB	0	8	2	888
DCBA	0	8	2	950

Table 3.1 also shows the sum of the positional differences between the letters of the study and test strings, which is called displacement. When displacement was added to the regression equation the correlation with different response time (RT) for Proctor and Healy's data increased to .97, $F(2,20) = 138$, $p < .001$.

The effect of matching left sequence implies that the different response is controlled by a serial, left-to-right comparison of the letters of the study and test strings that terminates when a mismatch is found. In addition, the effect of displacement implies that the mismatch signal from a single position is generated against the background of a signal whose strength is determined by the similarity between the study and test strings.

If the serial comparison process also controlled *same* judgments, then a *same* response would be made after comparisons at all four positions failed to generate mismatches. Hence, *same* responses would be slower than different responses. However, *same* responses were significantly faster than the fastest *different* responses. These fast *same* responses demonstrate that two different systems are responsible for the *same* versus *different* judgments.

The pattern of fast *same* responses and the speed of *different* responses as a function of left matching sequence is directly predicted by the dual-system theory. Fast *same* responses are made on the basis of a holistic comparison of the study and test strings across all four spatial positions. In other words, the test string is compared with a mental map of the study string and if they correspond across all four positions a fast match is generated. This spatial comparison process was shown to be controlled by the hippocampus-based instrumental system by Packard and McGaugh (1996).

At the same time as the holistic comparison begins, a serial left-to-right comparison of the individual letters of the study and test strings is initiated. If the simultaneous holistic spatial comparison fails to generate a large enough match signal to generate a *same* response and terminate both comparison processes, the serial comparison process continues until a mismatch is found and a *different* response is made. This serial comparison process is analogous to the sequential production of actions that Packard and McGaugh (1996) found to be controlled by the striatum-based habit system.

Though the instrumental system and the habit system operate in parallel, when the study and test string are identical the instrumental system generates a fast same response just as the serial comparison by the habit system has begun. Hence, a *same* judgment should be associated only with hippocampus activation, indicating only the instrumental system. When the study and test string are not identical, the magnitude of the matching response is insufficient to procedure a *same* response. Consequently, the serial comparison of each letter, associated with striatum activation, proceeds until a mismatch is found. So, if a different response is required, both the hippocampus and striatum are active, indicating the simultaneous processing of the test string by both the instrumental and habit systems. Hence, a *different* judgment should be coincident with activation of both the instrumental and habit systems.

The dual-system hypothesis therefore predicts that *same* responses should be associated solely with activation of the hippocampus, but *different* responses should be associated with activation of both the caudate and hippocampus.

3.3.1 Methods

Subjects performed the same/different matching task while being scanned in a 3T Siemens TRIO scanner at the Rutgers University brain imaging center (RUBIC).

Participants

Ten right-handed volunteers (7 female, 3 male; age range, 19–35 years) participated in the experiment and gave written informed consent before participation.

Materials

Each participant responded to 168 study-test string pairs. The pairs of four-letter strings were composed of uppercase consonants of the alphabet (excluding Y), with all letters used approximately equally often. No letter was repeated within a string. Hence, one of 20 x 19 x 18 x 17 = 116,280 study strings was randomly selected without replacement to begin each trial. Half (84) of the trials were *same* trials on which the study string was repeated as the test string and half of the trials were *different* trials on which a permutation of the study string was presented as the test string. There are 23 possible rearranged permutations of four-letter strings. All 23 possible arrangements of ABCD are shown in Table 2. The 84 string pairs in the *different* condition were divided among the 23 possible permutations of the four letters as show in Table 3.1: 24 with a left matching sequence of 2, 24 with left matching sequence of 1, and 36 with a left matching sequence of 0. Notice that Table 3.1 does **not** imply that any participant saw any string more than once because at the beginning of each trial a different study string was randomly selected. The two strings in each pair were centered immediately above and immediately below a fixation point that consisted of a pair of asterisks aligned with the middle two positions of the strings.

Procedure

Before testing, participants completed a short practice block to ensure that they understood the instructions and the task. Participants were scanned in a single session of the fMRI scanner. The fixation asterisks occurred as a warning signal for 0.5 sec. At their offset, the study string was presented for 1.5 sec, followed by a blank interval of 1 sec, and then the test string was presented for 3 sec. Subjects had to respond if the study string and test string were "same" or "different". Subjects were instructed to respond as quickly as possible without making an error, within the 3 sec interval during which the test string (probe) was presented, by pressing either the “same” or “different” button. Irrespective of the speed at which participants responded, the test string was presented for a fixed duration of 3 sec. The inter-trial interval was therefore fixed at 6 sec. Button labels were counterbalanced over subjects. Responses were collected via an MR-compatible two-button box. RT was measured from the onset of the test string. The string pair to be presented at each trial was selected from the 168 item list of test items constructed as described above.

fMRI acquisition

Imaging was performed on a 3T Siemens TRIO scanner at the Rutgers University Brain Imaging Center (RUBIC). Participants were scanned in the supine position and foam cushioning was used to stabilize head position and minimize head movement.

The stimuli were presented using PsychoPy (Peirce, 2007) software under the Windows XP operating system projected onto a back projection screen placed at the rear of the scanner bore. An MRI compatible two-button box was used for responses. Functional scanning was synchronized with the beginning of the experimental trials through a trigger pulse sent by the magnet to the PsychoPy software.

T1-weighted axial anatomical scans (TR = 1900 ms, TE =2.52 ms, field-of-view (FOV) = 256 mm, slice thickness 1 mm, 176 slices per slab) were obtained prior to the experimental trial sequence. These anatomical scans were used to register the functional imaging data. Functional imaging was done using an echo planar gradient echo imaging sequence and axial orientation. These scans were obtained using the following parameters: TR = 2000 ms, TE = 25 ms, FOV = 192 mm, slice thickness 3 mm, 33 axial slices covering the whole brain.

fMRI analysis

The fMRI data were analyzed using the FSL suite of programs (Jenkinson et al., 2012; Woolrich et al., 2009; Smith et al., 2004). BET (brain extraction tool) was used for skull stripping and removing non-brain tissues from both functional (BOLD) and anatomical images for each subject. General linear modeling (GLM) based analysis was performed on the functional data using the FEAT (FMRI Expert Analysis) software tool.

The first level FEAT analysis was performed for each subject. For this analysis, *same* judgments were contrasted with *different* judgments. Both activation for same>different and different>same were modeled. In addition, parametric changes were analyzed for the *different* judgments as a function of left matching sequence. Both increasing trends (increased activation with increased left matching sequence) and decreasing trends (increased activation with decreased left matching sequence) were modeled.

The first level individual subject analyses were used to perform a group level analysis across subjects. FLAME (FMRIB's Local Analysis of Mixed Effects) mixed-effects model was used with a with a cluster threshold of $p = .05$.

3.3.2 Results

Behavioral Data

Overall participants scored 96 % (SD = .192) correct in the *same* condition and 94% (SD = .234) correct in the *different* condition. For the *same* judgments, the reaction time was 900 milliseconds (SD = 227), while for different judgments, the reaction time was 1022 milliseconds (SD = 254). Furthermore, same judgments were significantly faster than different judgments, $t(9) = 2.726$, $p < 0.05$. Table 3.1 lists the reaction time as a function of left matching sequence for each of the 23 permutation types used in the *different* condition. The correlation between the length of the left matching string and different response time (RT) was .84. When displacement was added to the regression equation the correlation with different response time (RT) increased to .86, $F(2,20) = 27.8$, $p < .001$.

fMRI Data

First, we looked for clusters in the instrumental and habit systems where activity for *different* judgments was higher than that for *same* judgments. In the instrumental system, four clusters were identified, including left and right hippocampus and anterior parahippocampal gyrus (Figure 3.1 A, B; Table 3.2). Two clusters were identified in the habit system, including the left and right caudate (Figure 3.1 C; Table 3). Next, we looked for clusters in the instrumental and habit systems where activity for *same* judgments was higher than that for *different* judgments. In the instrumental system, three clusters were identified, including left posterior hippocampus and left and right posterior parahippocampal gyrus (Figure 3.2 A, B; Table 3.2). No clusters were identified in the habit system (Figure 3.2 C; Table 3.2).

Hence, consistent with the dual system hypothesis, *same* responses were associated with activation of the posterior hippocampus/parahippocampus, and *different* responses were associated with activation of both the caudate and anterior hippocampus/ parahippocampus. However, while the instrumental system was active for both *same* and *different* responses, there was a difference in the precise area of activation. As shown in Figure 3.1 and Figure 3.2, and again in Figure 3.3, *same* responses were associated with higher activation in the posterior hippocampal/parahippocampal region, and *different* responses were associated with higher activation in the anterior hippocampal/ parahippocampal region.

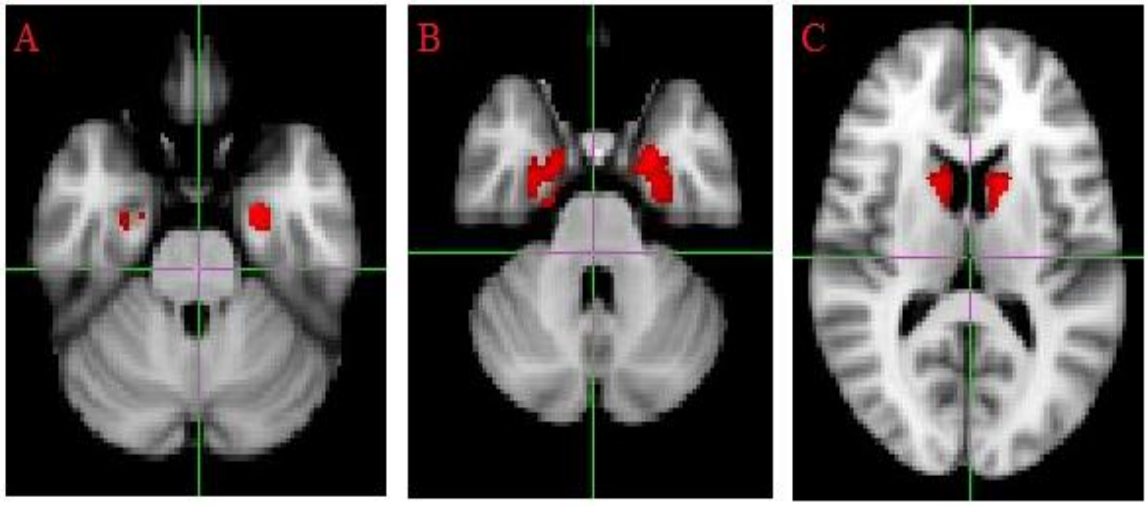

Figure 3.1. Clusters in the left and right hippocampus (A) and left and right anterior parahippocampal gyrus (B) of the instrumental system and left and right caudate (C) of the habit system were identified where brain activity was higher for *different* than for *same* judgments.

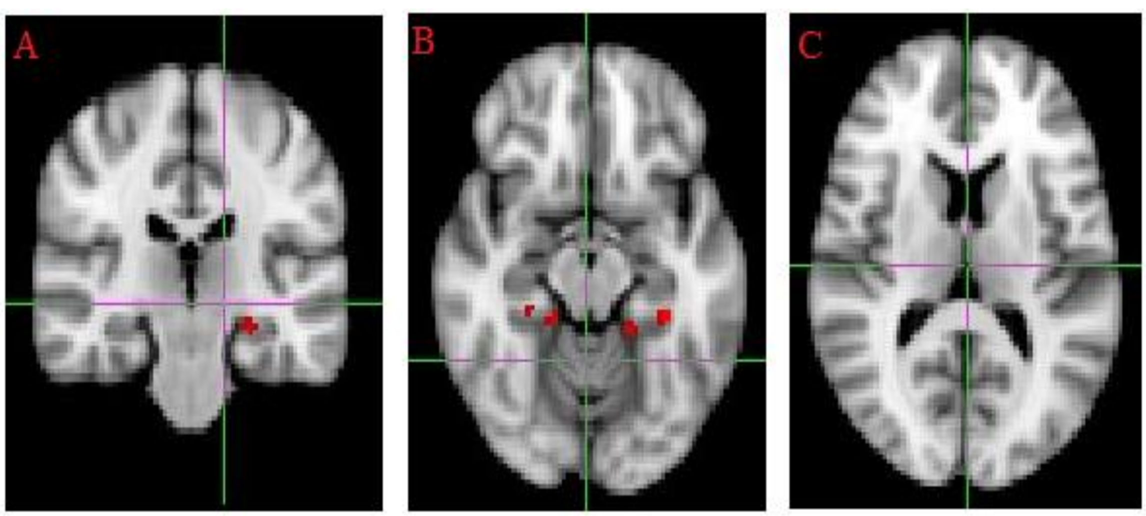

Figure 3.2. Clusters in the left hippocampus (A) and left and right posterior parahippocampal gyrus (B) of the instrumental system were identified where brain activity was higher for *same* than for *different* judgments. No clusters were identified in the habit system (C) for this comparison.

Table 3.2. *Instrumental and Habit system analysis.*

			MNI coordinates			Number	
			x	y	z	of Voxels	Intensity(Maximum)
Instrumental System	Different>Same (Figure 2 A, B)						
		L Hippocampus	-22	-4	-28	250	2.2
		R Hippocampus	10	-10	-18	110	1.8
		Anterior parahippocampal gyrus	26	-24	-24	679	2.5
	Same>Different (Figure 1 A, B)						
		L Hippocampus	-36	-34	-12	102	2.7
		Posterior parahippocampal gyrus	-36	-34	-12	329	2.7
Habit System	Different>Same (Figure 2 C)						
		L Caudate	-14	8	12	521	2.9
		R Caudate	12	12	8	426	2.8
	Same>Different (Figure 1 C)						
		No clusters found					

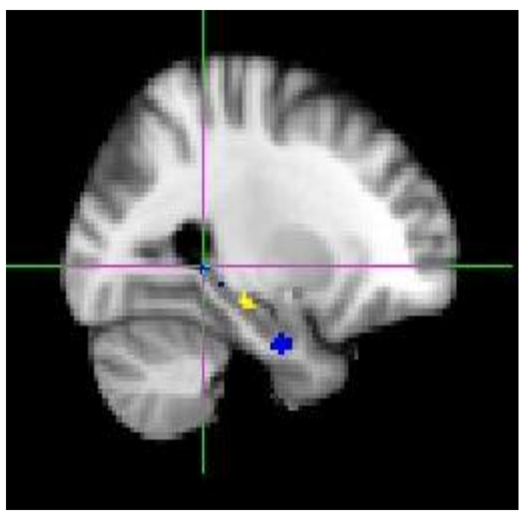

Figure 3.3. Same responses (in yellow) were associated with higher activation in the posterior hippocampal/parahippocampal region while *different* responses (in blue) were associated with higher activation in the anterior hippocampal/parahippocampal region.

We further analyzed *different* judgments to determine if there was a linear trend between activation in the instrumental and habit systems and the left matching sequence. The linear trend analysis included three levels of left matching sequence (0, 1 and 2). A positive linear trend was detected in the habit system, including the left and right caudate. Activation in these regions increased as the left matching sequence increased (Figure 3.4 A). A negative linear trend was also detected in the instrumental system, including the left and right hippocampus. Activation in these regions decreased as the left matching sequence increased (Figure 3.4 B).

This pattern of activation is consistent with the dual system hypothesis and is also reflected in the reaction time data. As the left matching sequence increases, the length of the study string that needs to be generated and compared with the test string by the habit system (in order to make a decision) increases. As a result, the involvement of the habit system increases while the involvement of the instrumental system decreases.

A negative trend was also observed in the left and right posterior parahippocampal gyrus, such that activation decreased with an increase in left matching sequence. Furthermore, the areas of activation coincided with clusters where activity for *same* judgments was higher than that for *different* judgments (Figure 3.5). This finding suggests that while the left and right posterior parahippocampal gyri are initially active for all test strings, if the initial surge in activation is not great enough to generate a *same* judgment and the serial comparison directed by the caudate proceeds, activation in these areas is inhibited and decreases (and as a result does not show up in the *different* > *same* contrasts).

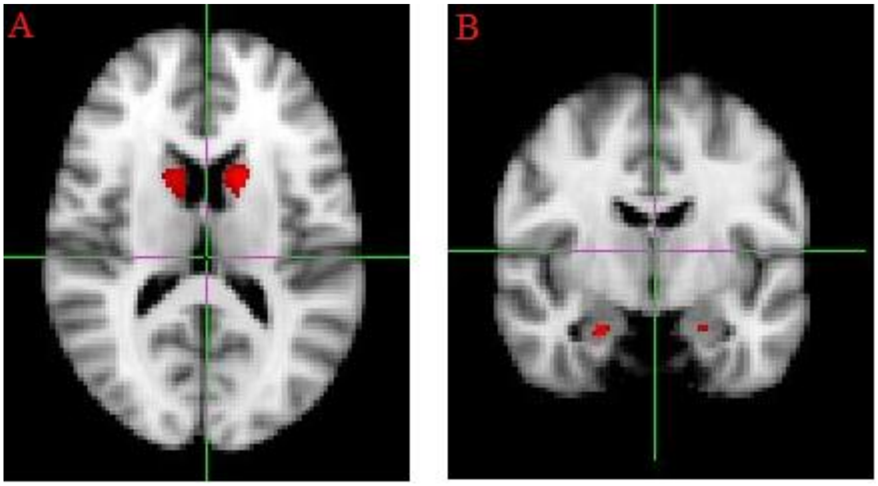

Figure 3.4. Activation in the left and right caudate increased as the left matching sequence increased (A). Activation in the left and right hippocampus decreased as the left matching sequence increased (B).

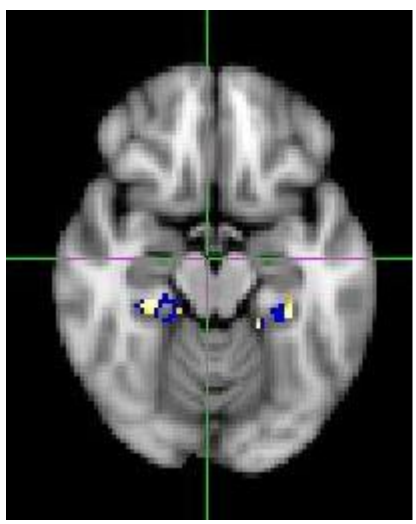

Figure 3.5. Activation in the left and right posterior parahippocampal gyri decreased with an increase in left matching sequence (in blue). The areas of activation coincided with clusters where activity for *same* judgments was higher than that for *different* judgments (in yellow).

Table 3.3. *Whole-brain analysis.*

		MNI coordinates x	y	z	Number of Voxels	Intensity(Maximum)
Different>Same						
	Inferior frontal gyrus pars triangularis (BA 45)	-56	22	28	3188	3.56
	Middle frontal gyrus/Inferior frontal gyrus pars opercularis (BA 46/44)	-56	20	28	2763	3.7
	Paracingulate (medial pre-frontal)/Superior frontal gyri	-2	22	46	2234	3.4
	L. Precentral/Postcentral gyri	-50	10	42	3443	3.6
	Anterior cingulate gyrus	4	32	34	1236	2.88
	Angular gyrus	-36	-56	52	2145	3.2
Same>Different	R. Precentral/Postcentral gyri	38	-18	50	3625	3.5
	Posterior cingulate gyrus	-16	-40	40	1583	2.5
	Precuneus	14	-54	-18	2627	2.8
	Cerebellum	-18	-56	-50	1383	2.3

Though Packard and McGaugh (1996) investigated only the role of the caudate, the habit system extends from the caudate into various structures in the prefrontal cortex (Yin and Knowlton, 2006). Consequently, we examined the whole-brain data, and identified several neocortical regions where activity for *different* judgments was higher than that for *same* judgments (Table 3.3). Consistent with Yin and Knowlton's (2006) description of the habit system, these regions were primarily prefrontal areas, the middle frontal/inferior frontal-pars triangularis gyri, inferior frontal-pars opercularis gyrus, and paracingulate/superior frontal gyri. Also, active were the left precentral/postcentral gyri, anterior cingulate gyrus and angular gyrus. In contrast, the neocortical regions that exhibited the opposite pattern, i.e., higher activity for *same* judgments than *different* judgments, the right precentral/postcentral gyri, posterior cingulate gyrus and precuneus, and the cerebellum, were not prefrontal areas (Table 3.3).

Connectivity Analysis

In order to estimate the causal relationships among the regions that increased in activation for *different* judgments, a connectivity analysis was conducted using graphical causal modeling with IMaGES (the Independent Multiple sample Greedy Equivalence Search) and LOFS (Linear non-gaussian Orientation, Fixed Structure) algorithms (Ramsey et al., 2010, 2011, 2014; Mumford and Ramsey, 2014) implemented using the TETRAD IV(version 5.0.0-1; http://www.phil.cmu. edu/projects/tetrad) software.

As elaborated in the previous section, *different* responses were associated with activation of the caudate, the hippocampus, the anterior parahippocampal gyrus and the pre-frontal cortex. Masks for each of the four regions of interest (ROI) were constructed. The mask for pre-frontal cortex was constructed by adding together individual components of the pre-frontal cortex where activation was detected for *different* judgments (Table 3.3). The time series from each ROI was extracted and then used as input to the IMaGES algorithm (Ramsey et al., 2010). Hence, each ROI was a node in the network whose connectivity we examined. The IMaGES algorithm searched for connections between the nodes (ROIs) and produced a directed acyclic graph (DAG).

After IMaGES identified a DAG for the set of regions, the DAG was fed to the LOFS algorithm (Ramsey et al., 2011). LOFS determined the direction of each connection. The results of the analyses are presented in Figure 3.6. The graph consists of nodes representing the ROIs and arrows that connect some of those nodes, depicting causal relationships between them. Hence, an arrow from region A to region B implies that changes in activation in the region A cause changes in activation in the region B.

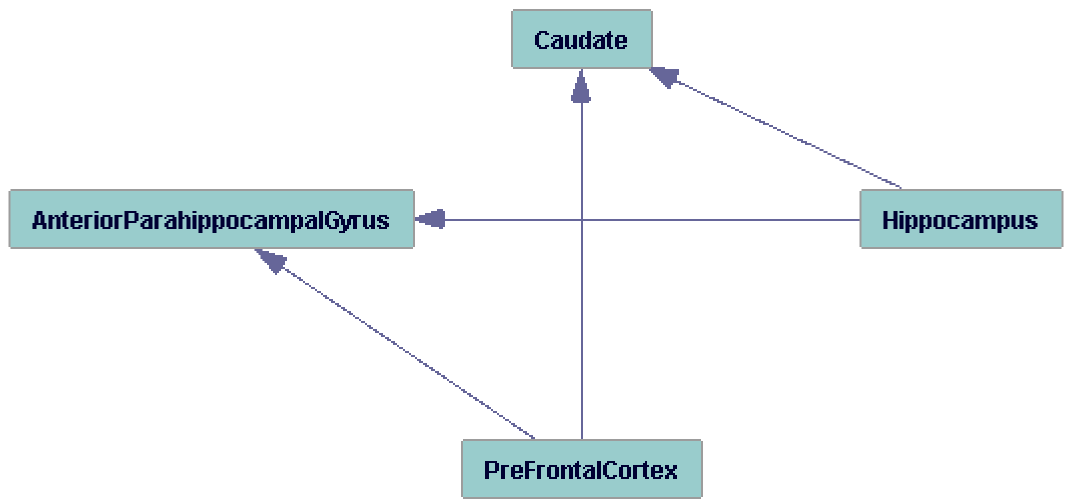

Figure 3.6. Directed acyclic graph showing inter-regional connectivity for *different* judgments.

Table 3.4 reports the mean and standard deviations of SEM coefficients across subjects. The connections between pairs of regions are in the left column. The directions of the connections are shown with the directed arrows"→."

3.3.3 Discussion

Taken together, the behavioral and neuroimaging results provide strong evidence for a dual-system explanation of the task . The causal IMaGES/LOFS analysis of the activation associated with *different* responses was somewhat more complicated than anticipated. Figure 3.6 shows functional links from the prefrontal cortex and hippocampus to the anterior parahippocampal gyrus and caudate. These functional links may indicate activation or inhibition; this information is not captured by the analysis. However, control is often exerted in the brain through inhibition. Therefore, while the two systems operate in parallel, the hippocampus initially inhibits activation of the caudate. When the study and test string are identical, the magnitude of the matching response produced by the hippocampus is sufficient to procedure a *same* response. Hence, a same judgment is

Table 3.4. *Inter-regional connectivity for different judgments.*

Edge	Mean	SD
Hippocampus →Caudate	0.3531	0.0099
Hippocampus→Anterior Parahippocampal Gyrus	1.0923	0.0119
PreFrontal Cortex→ Caudate	0.2425	0.0341
PreFrontal Cortex→ Anterior Parahippocampal Gyrus	-0.2446	0.0409

associated only with hippocampus activation. When the study and test string are **not** identical, the initial surge in activation (produced by the hippocampus) is not enough to generate a *same* response. Subsequently, the inhibition from the hippocampus to the caudate decreases, the activation of the caudate increases, and the serial comparison of each letter proceeds until a mismatch is found. Hence, a *different* judgment is coincident with activation of both the hippocampus and the caudate. Furthermore, an analysis of the linear trend between activation and the left matching sequence revealed that activation in the caudate increases while activation in the hippocampus decreases as the left matching sequence increases. This result is consistent with the assumption that when the serial comparison generates a mismatch, it is associated with activation of the caudate.

The joint control of caudate by the hippocampus as well as the prefrontal cortex is consistent with the finding that *different* RT is influenced by the overall similarity between the study and test strings as well the location of the different letter. The joint control of the anterior parahippocampal gyrus is consistent with the finding that areas that are active during *different* judgments are adjacent to the areas active during *same* judgments.

Dual System Hypothesis and the Dual Process Model of Recognition

The central purpose of this study was to determine if the dual-system hypothesis of memory can be extended to recognition judgments. Our findings suggest that the dual-system hypothesis does in fact provide a plausible neural explanation of the dual process model of recognition. As mentioned previously, using the *remember*/*know* procedure, several neuroimaging studies have found that activity in the hippocampus and parahippocampus is associated with both recollection and familiarity (Kirwan, Wixted and Squire, 2008; Smith, Wixted, and Squire, 2011; Wais, Squire and Wixted, 2010). This finding is consistent with the dual-system hypothesis and the results of this study, which found hippocampus activation during both *same* and *different* judgments.

Unfortunately, the possibility of different levels of caudate activation for *remember* versus *know* judgments was not investigated in these other studies. However, recall that the habit system includes prefrontal areas of the neocortex as well (Yin and Knowlton, 2006). Prefrontal activation was associated with *remember* (hence, recollection) but not *know* (hence, familiarity) judgments (Badre and Wagner, 2007; Kirwan et al., 2008; Ranganath and Blumenfeld, 2007; Wais et al., 2010), just as it was associated with *different* judgments but not *same* judgments, for the dorsolateral prefrontal cortex (middle frontal gyrus; approximately BA 46), ventrolateral prefrontal cortex VLPFC (inferior frontal gyrus pars opercularis/pars triangularis; approximately BA 44/45) and paracingulate (medial pre-frontal)/superior frontal gyri in this study. Hence, as per the dual-system hypothesis, familiarity is a kind of perceptual judgment that is associated with the instrumental system and the hippocampus, whereas recollection is based on the serial retrieval of details of the study episode, that is associated with the habit system and the caudate/prefrontal cortex.

Continuous Dual Process Accumulation Model

Integrating the dual-system hypothesis with dual process theory of recognition, we propose a dual process model of recognition called the Continuous Dual Process Accumulation Model (CDPA), which assumes that quick familiarity signals are based on perceptual judgments produced by the instrumental system, while the slower recollection signals require the habit system to generate the memory trace. On the presentation of a test item, the instrumental and habit systems work in parallel to generate the familiarity and recollection signals respectively. Since familiarity is available faster than recollection, if the familiarity (or novelty) signal produced by the hippocampus exceeds the old (or new) criterion, a quick perceptual high-confidence know-old (or new) decision is made. Otherwise, the old/new decision is made after the recollection signal has been generated by the habit system and the two components (recollection and familiarity) have been added to generate combined information. Furthermore, the model assumes that familiarity based know judgments involve just the instrumental system, while recollection based remember judgments involve both the instrumental and habit systems.

4. The Relationships among Accuracy, Confidence, and RT in Recognition: Evidence for the Continuous Dual Process Accumulation Model

Theories of recognition have shifted from a familiarity strength approach to a dual-process view, which distinguishes between knowing that one has experienced an object before and knowing what it was. Within the dual process framework, the debate between a segregated versus integrated view of recognition judgment is not yet settled. In fact, the boundaries between segregated and integrated models have become increasingly blurred. While Yonelinas's hybrid model started with recollection construed as a dichotomous high threshold process, post hoc explanations to account for partial recollections and remember false alarms have made it more consistent with a continuous criterion based view of recollection. On the other hand, while Wixted's single decision process model started with the concept of memory strength (as a combination of recollection and familiarity) which could not be segregated into individual components, it has been extended into a CDP model where the memory strength can be segregated into its recollection and familiarity components post recognition judgment.

Despite a lack of converging view in the field, all of the recent models can explain most of the extant results. However, there is one paradox in the data that is not convincingly addressed by any of the models, possibly because none of them were tested within a framework that unites confidence, accuracy and RT as dependent measures for remember and know responses. Response deadline and other procedures demonstrated that familiarity becomes available faster than recollection (Table 2.1, result 4). Since familiarity becomes available faster than recollection, and individuals can use remember/know judgments to report whether their decision was primarily based on recollection or familiarity, it should therefore follow that know judgments should be faster than remember judgments. This prediction contradicts the finding that remember responses are generally faster and associated with higher confidence than know responses (Table 2.1, result 11-17).

This paradox can be resolved by considering in more detail the time course of the two processes involved in making the recognition judgments, and the different information available to the subject when an initial speeded old/new response is made versus when a later remember/know judgment is made. In this chapter, we propose an integrated model called the Continuous Dual Process Accumulation (CDPA) model, that is consistent with the paradoxical findings that familiarity is available faster than recollection but remember responses are on average faster than know responses. As discussed in the previous chapter(section 3.3.3), the CDPA model uses the dual system hypothesis of memory as its neurological basis, assuming that quick familiarity signals are based on perceptual judgments produced by the instrumental system, while the slower recollection signals require the habit system to generate the memory trace. This allows the model to make informed predictions regarding the time course of recollection and familiarity and how the information available through these two processes is applied to make the recognition decision. The model can therefore explain the relationship between response time, accuracy and confidence for remember versus know judgments, as well as all of the other extant results.

We also present an experiment in which participants performed a conventional word recognition task and evaluate the RT, decision accuracy and source accuracy for remember and know responses in each confidence category to verify the predictions of the CDPA model.

4.1 Continuous Dual Process Accumulation Model

The CDPA model introduced here, is a revision of Atkinson-Juola model (Atkinson and Juola, 1974) along the lines suggested by Wixted and Mickes (2010). In fact, it is an extension of the continuous dual process (CDP) model proposed by Wixted and Mickes (2010). While all of the details of that model are assumed to be true here, there will be one elaboration. When testing the continuous dual process model (Wixted and Mickes, 2010; Ingram, Mickes and Wixted, 2012), participants were not asked to make recognition judgments under time pressure and therefore the model did not consider how rapidly familiarity and recollection accumulated in response to a test. The model will be elaborated to assume that familiarity accumulates more rapidly than recollection, as originally proposed by Atkinson and Juola (1974). By adding this assumption, it will be possible to extend the predictions of the continuous dual process model to speeded recognition tasks. Furthermore, with this assumption, the speeded recognition task provides another method besides remember/know judgments for distinguishing between the effects of familiarity and recollection on recognition.

According to the CDPA model, recognition decisions are made on the basis of two kinds of information, (familiarity and/or recollection), produced in response to an item. A perception of familiarity and/or recollection of contextual details associated with a target constitute positive information, which results in an "old" response (the item is identified as a target). On the other hand, a perception of novelty and/or recollection of information corroborating that the item was not on the study list, but encountered elsewhere, constitutes negative information, which results in a "new" response (the item is identified as a distracter).

Figure 4.1 illustrates the CDPA model. As shown in Figure 4.1 A, the model consists of an old criterion and a new criterion along the y-axis that represents the accumulation of information over time. The x-axis represents response time. If at any time the accumulated information exceeds either criterion, the appropriate response is made. If the positive information exceeds the old criterion, an "old" response is made, and if the negative information exceeds the new criterion, a "new" response is made. Over time, the criterion for a response becomes more lenient. The two criteria slope towards each other so that they eventually meet at the starting point (Bowman, Kording and Gottfried, 2012; Cisek, Puskas, and El-Murr, 2009; Ditterich, 2006; Thura, Beauregard–Racine, Fradet, and Cisek, 2012). Consequently, the amount of information required to make a response declines over time. The meeting of the two criteria marks the deadline. If neither the old nor the new criterion has been exceeded for an item at the deadline, the probability of selecting an "old" (or "new") response matches the percent of previous "old" (or "new") responses. Hence, the amount of information accumulated for an item is negatively correlated with response time, such that , a large amount of positive information results in fast "old" responses and a large amount of negative information results in fast "new" responses.

As shown in Figure 4.1 B, confidence criteria are also placed along the accumulated information axis. The old and new criteria represent the points of highest confidence. The point at which the information associated with the item (positive or negative) exceeds either criterion, determines the confidence ("old" or "new") associated

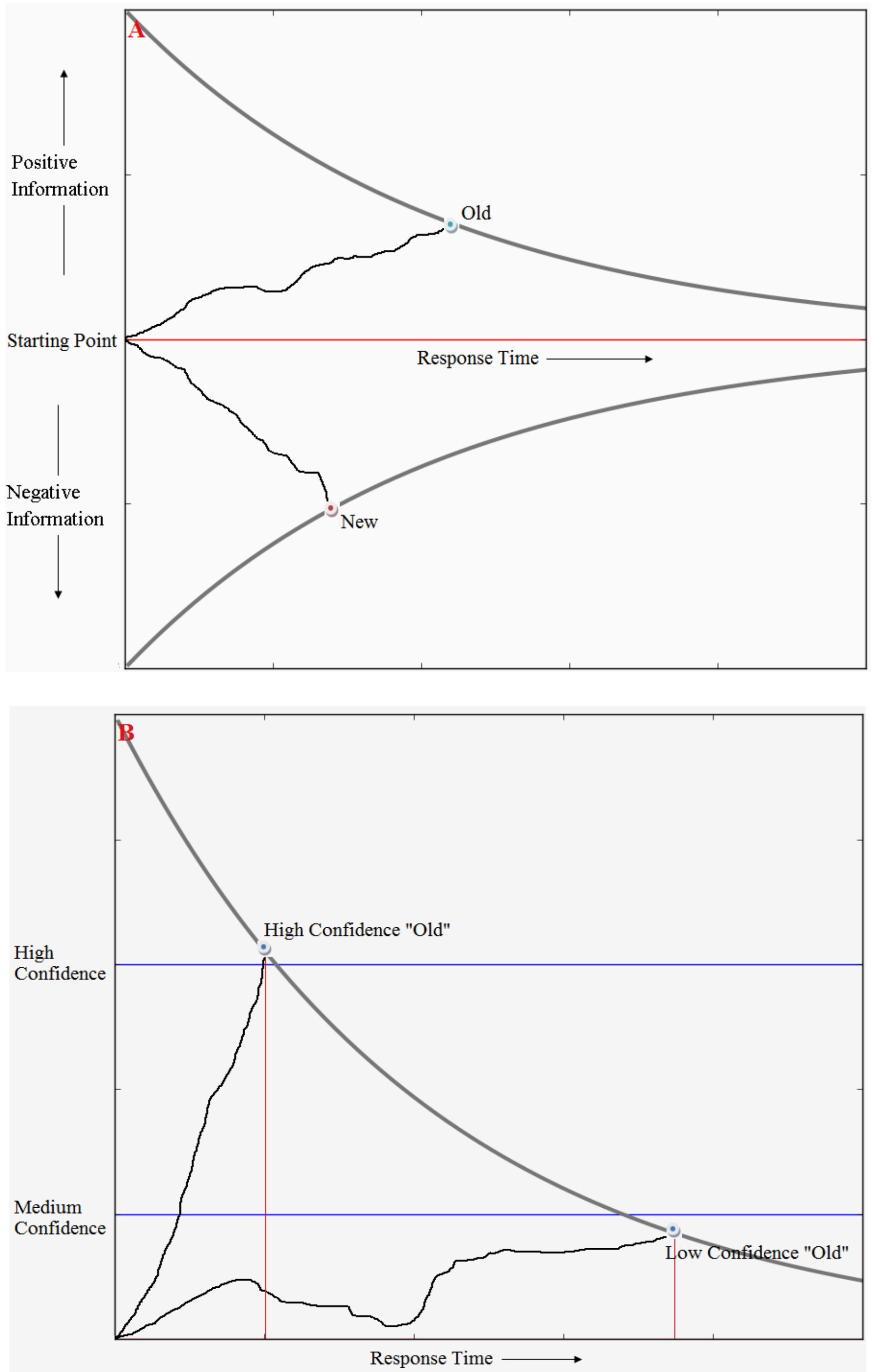

Figure 4.1. An illustration of the continuous dual process accumulation (CDPA) model. Over time, the old (and new) criteria slope towards each other, and the point at which the accumulated information meets the criteria, determines the confidence and RT associated with the response. A large amount of positive (or negative) information results in fast high confidence "old" (or "new") responses.

with the response. If neither criterion (old or new) has been exceeded by the time the old and new criteria meet at the deadline, a low confidence response is made. Confidence in a response is therefore positively correlated with the amount of information used to make a response.

Hence, the amount of information (whether positive or negative) is positively correlated with confidence and negatively correlated with response time. A large amount of positive information results in fast high confidence "old" responses and a large amount of negative information results in fast high-confidence "new" responses.

Two kinds of information are used to make an old/new response, familiarity and recollection. First, when an item is presented for recognition, the familiarity of the item is generated as part of the perceptual experience of the item. If the perceived familiarity of the item exceeds the old criterion then a fast high-confidence “old” response is made for the item. If the perceived novelty of the item exceeds the new criterion then a fast high-confidence “new” response is made for the item. Familiarity is part of the perceptual experience of an item, and is hence rapidly generated. When the rapidly generated high familiarity signal exceeds the old response criterion or the high novelty (i.e. low familiarity) signal exceeds the new response criterion, these judgments will be fast and associated with high-confidence. Hence, familiarity by itself can provide enough information to exceed the old or new criterion. In addition to making old/new responses, participants may be asked to make post-response, remember/know judgments. When, the old/new response is based on familiarity alone and a post-response recollection of the test item does not accumulate, the observer categorizes it as a know judgment.

If the familiarity of the test item is between the old criterion and the new criterion, recollection is incorporated and the old/new response is based on the sum of recollection and familiarity. We will refer to this sum of recollection and familiarity as aggregated information. As mentioned previously, the aggregated information could be positive information associated with a target or negative information associated with a distracter. If the positive aggregated information exceeds the old criterion, an "old" judgment is made. If on the other hand, the negative aggregated information exceeds the new criterion, a "new" judgment is made.

If no recollected data is accumulated and the aggregated information consists of just the previously accumulated familiarity, a low confidence know judgment will be made, at (or close to) the deadline.

Therefore, the CDPA model assumes that the fastest and slowest old/new responses will be based on familiarity. Hence, in this model there are two kinds of know judgments, fast high-confidence know judgments and slow low confidence know judgments that are both devoid of any recollection and so are based on familiarity. In contrast, recollection accumulates more slowly than familiarity, but increases the aggregated information, hence increasing the likelihood that the criterion will be exceeded before the deadline. So, either a high or low confidence judgment will be made depending on how close to deadline the aggregated information exceeded the response criterion.

Responses to those test items that elicit some degree of recollection are called “remember” responses by the subject and include all responses in the middle of the response time distribution. If there is no recollection of the test item it will be categorized by the subject as a “know” response.

However, in the CDPA model, remember judgments following high-confidence, “old” responses may be based on either pre or post-response information. In the speeded recognition task, it is assumed that recollected information continues to accumulate even after a fast “old" response has been made for a familiar test item. Though this additional recollected information did not influence the “old” response, it may influence the post response, reflective, remember/know judgment that is not made under time pressure and cause the response to be categorized as a “remember” judgment. This implies that a number of high-confidence, fast, familiarity-based responses, which should have been categorized as know responses, get incorrectly categorized as remember responses on the basis of post-response recollection. Even though the old/new response may have been made purely on the basis of familiarity, enough recollected data might accumulate in the time between the old/new response and the remember/know judgment, that the response may be categorized as a remember judgment instead of being (correctly) categorized as a know judgment. We will call these remember judgments post-recognition, high-confidence, remember-judgments. On the other hand, high-confidence remember-judgments are also made when recollected information accumulates before the old/new response is made. In this case, the presence of recollection data in the aggregate information causes it to exceed a criterion and forms the basis of an old or new response. This response is correctly categorized as a remember judgment. We will call these judgments pre-recognition high-confidence remember judgments.

So, in the speeded recognition task, confidence is inversely correlated with response time, such that all high-confidence judgments are made faster than low confidence judgments. However, an important distinction predicted by the model is that pre-recognition high-confidence remember judgments will be slower than the high-confidence know judgments since these remember judgments involve the accumulation of recollection data over time. The model also predicts that post-recognition high-confidence remember judgments will have the same response times as the fast high-confidence know judgments, since these remember judgments are essentially misclassified know responses.

Even though the CDPA model predicts that the fastest old/new responses will be based on familiarity, it also predicts that the slowest old/new responses will be based on familiarity and that some of the fastest old/new responses will be mischaracterized as "remember" judgment. The CDPA model therefore explains why the mean response time for "remember" responses is faster than for "know" responses when confidence is not taken into account. Because the response time distribution is skewed, including a tail of slow responses, mean response time for "know" responses is greater than mean response time for "remember" responses. Hence, the model reconciles the empirical finding that familiarity is available faster than recollection with the contrary finding that "remember" responses are generally faster than "know" responses.

4.1.1 Quantitative Description of the CDPA Model

The quantitative version of the CDPA model is a collapsing bound diffusion model with two independent processes (recollection and familiarity), and can be seen as an extension of the diffusion model approach introduced by Ratcliff (1978), as a tool for analyzing data from speeded response time.

As discussed in Chapter 2, there is a large and well-developed set of competing dual process models that account for accuracy and confidence in decision-making (Kelley and Wixted, 2001; Rotello et al., 2004; Wixted and Mickes, 2010). However, to develop a finely detailed processing model, it is essential to draw upon the composition of response time distributions in addition to accuracy and confidence from recognition judgment tasks. The CDPA model attempts to generalize signal detection theory to also account for response times, by incorporating a diffusion process. The basic assumptions of the diffusion process are that information accumulates continuously and that the accumulation of information can be described by a Wiener diffusion process. This Wiener diffusion process is characterized by a normally distributed drift/accumulation rate. The mean drift rate determines the average slope of the information accumulation process, that is, the speed and direction of information accumulation. The assumption of a variable, normally distributed drift rate implies that repeated processing of the same stimulus across different trials will yield variable response times, and may sometimes lead to different (i.e., erroneous) classification responses.

The CDPA model assumes that decisions are made by two independent noisy processes (recollection and familiarity) that accumulate information over time from a starting point (z_0) toward one of two (old or new) response criteria or boundaries. The rate of accumulation of information or drift rate for the two processes is assumed to be normally distributed for both targets and distracters and is represented as:

- Recollection process for targets: $R \sim N\left(\mu_R t, \sqrt{2D_R t}\right)$

- Familiarity process for targets: $F \sim N\left(\mu_F t, \sqrt{2D_F t}\right)$
- Recollection process for distracters: $R_0 \sim N\left(\mu_{R_0} t, \sqrt{2D_{R_0} t}\right)$
- Familiarity process for distracters: $F_0 \sim N\left(\mu_{F_0} t, \sqrt{2D_{F_0} t}\right)$,

where D_A represents the diffusion constant for process *A*, and t represents the duration of the elapsed time interval. Conceptually, the drift rate represents the quality of the match between a test stimulus (word) and memory. Therefore, higher the degree of match with memory for a test word, higher the drift rate, and hence greater the accumulated information associated with that word. Furthermore, as mentioned previously, the assumption of normally distributed drift rate implies that there is inter-trial variability, such that the amount of accumulated information might not be exactly the same for each trial of the experiment, either because of fluctuations of the participant's attention, or because of differences in stimuli.

For each target (or distracter) both the recollection and familiarity processes accumulate information, which is then combined together in order to make a decision. Because the two processes accumulate information independently, the overall drift rate is distributed as

$$X = R + F \sim N\left(\mu(t), \sigma(t)\right), \text{ where}$$

$$\mu(t) = \mu_R t + \mu_F t \tag{1}$$

$$\sigma(t) = \sqrt{2t\left(D_R + D_F\right)}$$

As shown in Figure 4.1 A, when this combined accumulated information reaches one of the boundaries (old or new), a response is initiated. The boundaries start at some high point *B* (or -*B*) and collapse exponentially (at rate τ) over time towards the starting point z_0 . The location of the boundary at any time *T* is denoted as *B(T)*. Hence, the point at which the accumulated information meets the boundary determines the response time associated with the response. Evidence for such a collapsing bound has been reported by several studies (Bowman, Kording and Gottfried, 2012; Cisek, Puskas, and El-Murr, 2009; Ditterich, 2006; Thura, Beauregard–Racine, Fradet, and Cisek, 2012) and has been interpreted both in terms of the reduced impact of incremental information in the face of substantial accumulated evidence (Bowman et al.,,2012; Ditterich, 2006; Hanks et al., 2011) and in terms of the effect of an increase in temporal urgency signal (Cisek et al., 2009; Thura et al., 2012).

Solving the collapsing-bound model for response time distributions is not analytically tractable. However, by using discrete time-steps and assuming that the accumulation of information occurs at these discrete points in time, we can get approximate distributions, as follows:

After an initial interval of T_0 seconds has elapsed, the probability that the accumulated information associated with a response reaches location X_{T_0} , having originated at starting point z_0 , is given by a Gaussian distribution,

$$p_{T_0}\left(X_{T_0}\right) = \phi\left[\frac{X_{T_0} - (\mu(T_0) + z_0)}{\sigma(T_0)}\right] \tag{2}$$

At each further time point $T + t$, the proportion of responses for which the associated accumulated information reaches some location X_{T+t} , can be computed by multiplying the probability of each location $X_T < B(T)$ that did not exceed the bound at the previous time-step by the conditional probability of its current position given that it was at location X_T in the previous time-step and marginalizing over this previous location.

$$p_{T+t}\left(X_{T+t}\right)=\int_{-\infty}^{B(T)} p_T\left(X_T\right)p\left(X_{T+t}\mid X_T\right)dX_T \tag{3}$$

Because the conditional distribution of drift rates is independent of starting location, this is equivalent convolving the location distribution at the previous time point *T*, with the probability of drift defined in Eqn. (2).

$$\begin{aligned} p_{T+t}\left(X_{T+t}\right)&=\int_{-\infty}^{B(t)} p_T\left(X_T\right)\phi\left[\frac{X_{T+t}-(X_T+\mu(t))}{\sigma(t)}\right]dX_T \\ &= p_T\left(X_T\right)\otimes\phi\left[\frac{\Delta X-\mu(t)}{\sigma(t)}\right],\quad X_T<B(T) \end{aligned} \tag{4}$$

The proportion of "old" responses at a given time *T* is then obtained by summing together responses for which the accumulated information exceeds the boundary at time *T*,

$$p_T\left(\text{old}\right)=\int_{B(T)}^{\infty} p_T\left(X_T\right)dX_T \tag{5}$$

As mentioned previously, the model assumes that the recollection and familiarity processes accumulate information independently, which is then combined together in order to make an old/new decision. This is illustrated in Figure 4.2, where the x-axis represents recollected information, the y-axis represents familiarity information and the z-axis represents the total (sum) accumulated information. In order to make post-response remember/know judgments, the information accumulated by the recollection process is checked against an internal recollection criterion B_r (placed along the recollection x-axis). The location of the recollected information at time T, given that the total

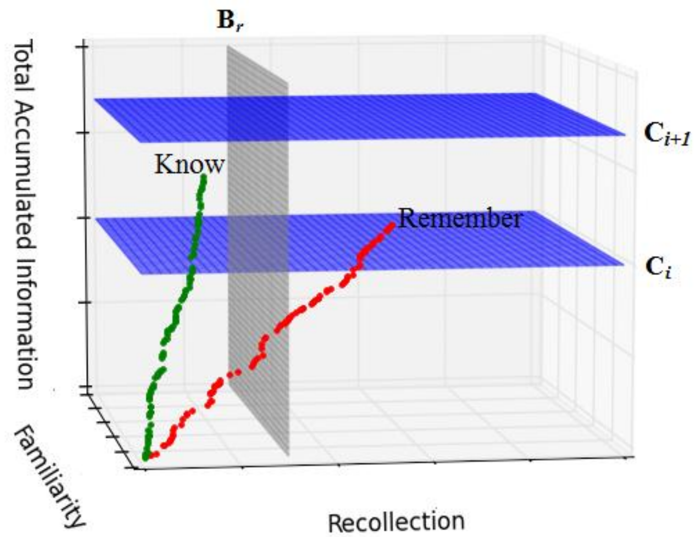

Figure 4.2. Recollected information accumulates along the recollection axis, familiarity information accumulates along the familiarity axis. If the recollected information for an "old" decision exceeds B$_r$ it is classified as a remember judgment, otherwise it is classified as a know judgment. Confidence criteria placed along the (total) accumulated information axis determine the confidence associated with the response.

accumulated information was at location X_T, is determined by the drift rate for the recollection process at that time, which is distributed as,

$$
\begin{aligned}
R_T &\sim N\left(\mu_{R|X}(T), \sigma_{R|X}(T)\right), \text{ where,} \\
\mu_{R|X}(T) &= E_R\left[R_T \mid X_T\right] \\
&= \mu_R T + \left(X_T - \mu(T) - z_0\right)\frac{\sigma_R^2}{\sigma^2} \\
\sigma_{R|X}^2(T) &= Var\left[R_T \mid X_T\right] \\
&= \sigma_R^2\left(1 - \frac{\sigma_R^2}{\sigma^2}\right),
\end{aligned}
\tag{6}
$$

where R_T represents the information accumulated by the recollection process and X_T represents the total accumulated information (combined across both processes) at time T.

If the information accumulated by the recollection process exceeds B_r, the response is categorized as a remember judgment. The probability that accumulated recollected information exceeds the criterion B_r is,

$$p_T(R_T > B_r) = \int_{B_r}^{\infty} \phi\left[\frac{B - \mu_{R|X}(T)}{\sigma_{R|X}(T)}\right] dB \tag{7}$$

On the other hand, if the recollected information falls below B_r, it implies that the old/new decision was made largely on the basis of accumulated familiarity information. In this case, a know judgment will be made. We therefore have,

$$p_T(R_T < B_r) = \int_{-\infty}^{B_r} \phi\left[\frac{B - \mu_{R|X}(T)}{\sigma_{R|X}(T)}\right] dB \tag{8}$$

If the old/new decision is made at time *T*, a small time interval δ_T elapses before a confidence judgment is made. In this interval δ_T, a small amount of additional information accumulates. In order to determine the confidence rating associated with the response, the total accumulated information at time $T + \delta_T$ is compared against confidence bounds (C_i). The location of the total accumulated information is determined by the overall drift rate at that time, which is distributed as,

$$X_{T+\delta_T} \sim N\left(\mu(T+\delta_T), \sigma(T+\delta_T)\right), \text{ where}$$

$$\mu(T+\delta_T) = \mu(\delta_T) + X_T, \text{ and} \tag{9}$$

$$\sigma(T+\delta_T) = \sqrt{2\delta_T\left(D_R + D_F\right)}$$

As shown in figure 4.2, the confidence criteria are placed along the z-axis, which represents the total accumulated information. The proportion of remember responses, made with confidence C_i, at a given time T is then obtained by determining the proportion of "old" responses, for which the recollected information exceeds the criterion B_r (at time *T*), that fall between confidence criteria C_i and C_{i+1} at time $T+\delta_T$. Hence, at time *T*, the proportion of remember responses made with confidence C_i is,

$$p_T\left(remember \mid C_i\right) = p_T(old)\,p_T(R_T > B_r)\int_{C_i}^{C_{i+1}} \phi\left[\frac{C-\mu(T+\delta_T)}{\sigma(T+\delta_T)}\right]dC \tag{10}$$

Similarly, the proportion of "old" responses for which the total accumulated information is between confidence criteria C_i and C_{i+1}, and the corresponding recollected information falls below B_r comprise know responses made with confidence C_i,

$$p_T\left(know \mid C_i\right) = p_T(old)\,p_T(R_T < B_r)\int_{C_i}^{C_{i+1}} \phi\left[\frac{C-\mu(T+\delta_T)}{\sigma(T+\delta_T)}\right]dC \tag{11}$$

The overall proportion of remember and know responses is computed as,

$$\begin{aligned} P(remember) &= \sum_i^{C_i}\int_0^{\infty} p_T(remember \mid C_i)\,dT \\ P(know) &= \sum_i^{C_i}\int_0^{\infty} p_T(know \mid C_i)\,dT \end{aligned} \tag{12}$$

4.2 Experimental Tests of CDPA Model

The most direct way to investigate the validity of the continuous dual process accumulation model is to determine whether fast, high-confidence, “know” judgments exist. A central assumption of the CDPA model is that high-confidence “know” judgments are made when the faster familiarity signal is strong enough to exceed a criterion, and pre-recognition high-confidence “remember” judgments are made only after the slower recollected information becomes available and is combined with the already available familiarity (which was not strong enough to surpass the criterion). Therefore, the model predicts the occurrence of fast high-confidence “know” judgments that are on average faster than pre-recognition high-confidence “remember” judgments, while having approximately the same old/new accuracy.

Because high confidence, “know” responses only follow fast familiarity judgments but high confidence, “remember” judgments follow both fast familiarity responses (when post-response recollection occurs) and slower recollection response, the model also predicts that the variability of the high confidence, “know” judgments will be less than the variability of the high confidence, “remember” judgments.

The model further assumes that when there is neither high familiarity nor recollection, so that the response is made at deadline, it is classified as a low confidence “know” judgment on the basis of the lack of recollection. The slowest responses will therefore be characterized by the subjects as low confidence, “know” judgments. Since low confidence “remember” judgments will have always been made if the criterion was exceeded but low confidence “know” judgments will include responses made at deadline, low confidence “know” judgments will be slower than low confidence “remember” judgments.

Hence, the model predicts a mirror effect for “know” versus “remember” judgments, with fast high-confidence “know” judgments faster than high-confidence “remember” judgments and slow low-confidence “know” judgments slower than low-confidence remember judgments. Furthermore, since the fastest and slowest old/new responses will be “know” responses based on familiarity there will be a skewed response time distribution for “know” responses with a greater standard deviation and a larger mean than for “remember” responses.

Therefore, the CDPA model makes four predictions not made by the CDP model. First, because high familiarity is perceived before recollection, high confidence, “know” judgments will be faster than high confidence, “remember” judgments. Second, because the fastest high confidence, “remember” judgments are the result of the post-recognition accumulation of source information, while slower high confidence “remember” judgments result when source information accrues before the recognition (old/new) decision, the variability of high confidence “remember” judgments will be greater than the variability of high confidence “know” judgments. Third, because for a low confidence response to be characterized as “remember” responses require the accumulation of sufficient source information to exceed the response criterion but low confidence responses characterized as “know” responses include the slowest responses made at the deadline, low confidence “know” responses will be slower than low confidence “remember” judgments. Fourth, since the fastest and slowest old/new responses are “know” responses resulting in a skewed response time distribution for these responses, overall the variability of “know” judgments will be greater than that of “remember” judgments.

To test these predictions, an experiment was done in which the procedure closely modeled that of Wixted and Mickes (2010) and Ingram, Mickes and Wixted (2012). However, in this experiment, speeded old/new judgments were made and response time was analyzed with confidence as a factor. This made it possible to determine whether the results were consistent with previous findings, in addition to testing the four predictions of the CDPA model.

4.2.1 Method

Participants

Thirty-one undergraduates from Rutgers University, New Jersey participated for psychology course credit.

Materials

Participants were asked to study a list of words for a later memory test. The word pool from which the list items were drawn consisted of 620 four-to-seven letter words generated from the medical research council Psycholinguistic Database (Coltheart, 1981), with the additional constraints of ratings between 500 and 700 for familiarity, imaginability, and concreteness. From the word pool 272 words were randomly selected, with 128 words assigned as targets and 128 words assigned as lures. The remaining 16 words were randomly divided between targets and lures and used during the practice phase. The 128 target words used in the study were divided into 4 subsets such that the set had on average 5 letter words and approximately equal mean ratings for familiarity, imaginability, and concreteness.

Procedure

The study consisted of two phases, study and test. During the study phase, 128 target words were presented for 2.5s at a time on the screen, in either red or blue and on the top or the bottom of the screen. The 31 subjects were divided into 4 groups (three of which had 8 subject while one had 7 subjects) in order to counter-balance the word list for the source attributes using a lattice square design.

The test phase followed the study phase. In the test phase, subjects were shown all the 128 words from the study list (targets) intermixed with 128 new words (distracters). At test, each word was presented in black at the center of the screen. For each word, subjects had to make an old/new judgment. Subjects were instructed to judge words previously shown in the study phase as old and words not shown in the study phase as new. Subjects were also told to respond as fast as they could without making an error. As soon as the subject responded, the word disappeared from the screen. Reaction time for the old/new response was measured.

For each item, subjects were asked to make an old/new confidence rating on a [0, 6] rating scale (0 = *guess old/new*, 6 = *certain old/new*). Following confidence ratings, for each item judged to be old, subjects were asked to make a dichotomous remember/know judgment. Finally, subjects were asked two source questions, whether the word was presented on the study list in red or blue and whether the word was presented in the study list on the top or the bottom of the screen. Each subject made a location judgment first for half of the test items and a color judgment first for half of the test items.

4.2.2 Results and Discussion

Overall for "old" recognition judgments, confidence and old/new accuracy were positively correlated, $r(29) = .423$, $p < .05$. Analyzed separately, confidence and old/new accuracy were positively correlated for both “know” ($r(29) = .514$, $p < .05$) and “remember” judgments ($r(29) = .635$, $p < .001$).

Figure 4.3 A shows the old/new accuracy and source accuracy for “remember” and “know” judgments. Old/new accuracy for “remember” judgments (80%, S.D = 16.8) was significantly higher than that for “know” judgments (64.5%, S.D = 16.7), $t(30) = 3.2$,

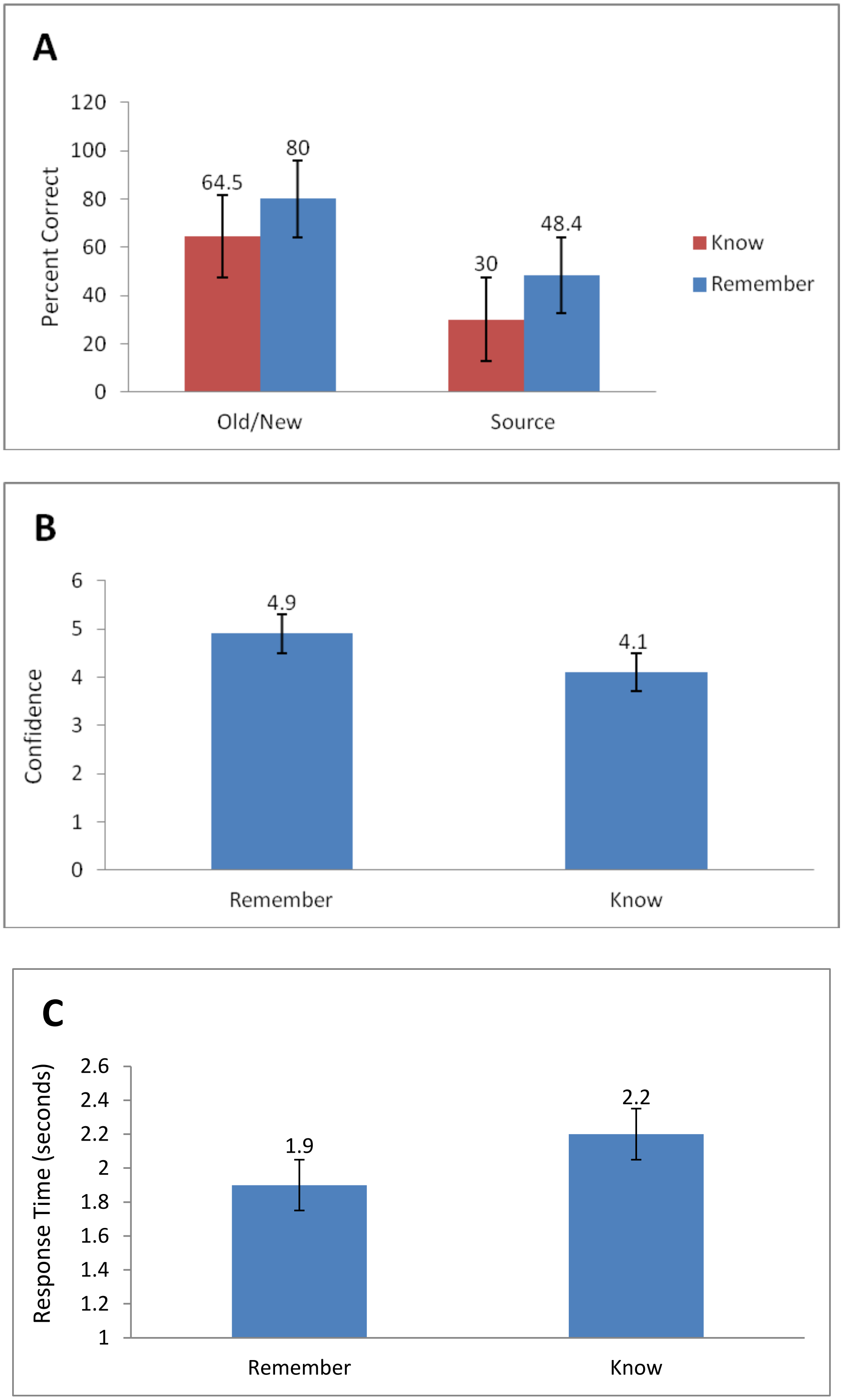

Figure 4.3. Mean old/new and source accuracy (A), confidence (B) and response time (C) for remember and know responses.

$p < .05$. Furthermore, source accuracy for “remember” judgments (48.4%, S.D = 17.4) was significantly higher than that for “know” judgments (30%, S.D = 23), $t(30) = 3.8$, $p < .001$. Figure 4.3 B shows the confidence ratings for “remember’ and “know” responses. “Remember” judgments (4.9, S.D = .91) were given significantly higher confidence ratings than know judgments (4.1, S.D = 1.09), $t(30) = 3.04$, $p < .05$. These results replicate the findings of Tulving (1985), Stretch and Wixted (1998), Dobbins, Kroll and Liu (1998) and Heathcote, Freeman, Etherington, Tonkin and Bora (2009), that “remember” judgments were more accurate and confident than were “know” judgments.

Figure 4.3 C shows the average reaction time for “remember” and “know” judgments. “Remember” responses (1.9s, S.D = .76) were faster than “know” responses (2.2s, S.D = 1.03), as was found by Dewhurst and Conway (1994), Wixted and Stretch (2004), and Dewhurst, Holmes, Brandt and Dean (2006), but unlike the previous results, the difference was not significant, $t(30) = 1.63$, $p = .11$.

For a more detailed analysis, responses were segregated into high, medium and low confidence “remember” responses and high, medium and low confidence “know” responses. Judgments given a confidence rating of 5 or 6 were considered high confidence judgments, judgments given a confidence rating of 2, 3 or 4 were considered medium confidence judgments and judgments given a confidence rating of 0 or 1 were considered low confidence judgments. The main comparisons of interest were (a) between “remember” and “know” "old" decisions that were made with high confidence and (b) between “remember” and “know” "old" decisions that were made with low confidence.

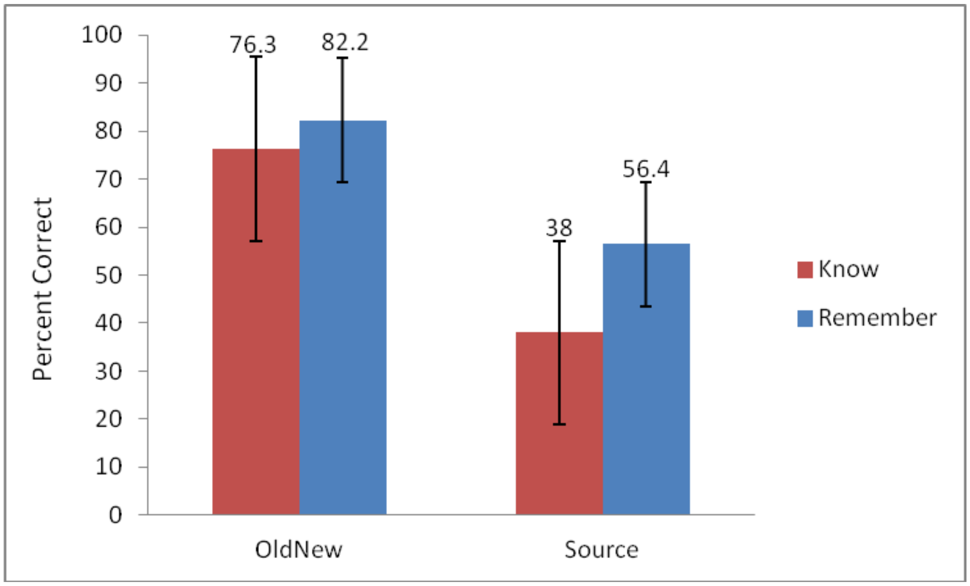

Figure 4.4. Old/new accuracy and source accuracy for high confidence “know” and “remember” responses.

Data from 25 of the 31 participants who made at least one high confidence response in both “remember” and “know” categories was analyzed. Figure 4.4 shows the old/new accuracy and source accuracy for these high confidence responses. The old/new accuracy associated with “remember” judgments was 82.2% (S.D = 14.5) and accuracy associated with “know” judgments was 76.3% (S.D = 18), and the difference between them did not approach significance. However, source accuracy associated with high confidence “remember” responses (56.4%, S.D = 17.3) was significantly higher than that for high confidence “know” judgments(38%, S.D = 24.5), $t(24)= 3.97$, $p < .001$. Therefore high confidence “know” judgments had approximately the same old/new accuracy but much lower source accuracy, which replicates the pattern observed previously by Wixted and Mickes (2010) and Ingram et al. (2012).

Figure 4.5 shows response times for high confidence "old" “remember” and “know” responses collapsed over targets and distracters (overall), to targets alone (hits)

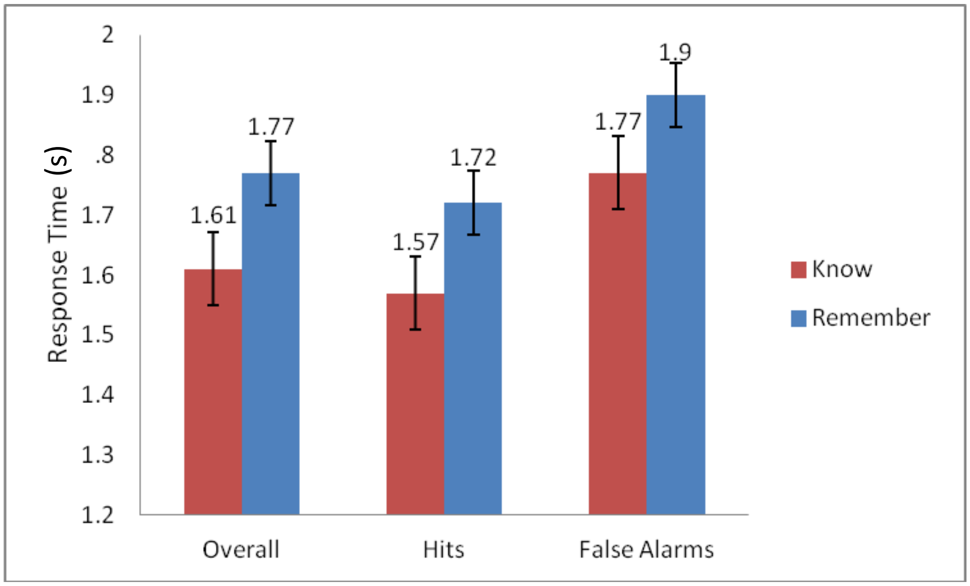

Figure 4.5. Mean response time for high confidence "know" and "remember" responses collapsed over targets and distracters (overall), to targets alone (hits) and to distracters alone (false alarms).

and to distracters alone (false alarms). Response time for high confidence "know" judgments (1.61s, SD = .57) was significantly faster than response time for high confidence "remember" judgments (1.77s, S.D = .7), $t(24) = 2.26$, $p < .05$. Response time data was then separately analyzed for hits and false alarms. High confidence "know" hits (1.57s, S.D = . 56) were significantly faster than high confidence "remember" hits, (1.72s, S.D = .65), $t(24) = 2.06$, $p < .05$. While high confidence "know" false alarms (1.77s, S.D = .8) were faster than high confidence "remember" false alarms (1.9s, S.D = .85), the difference was not significant. Hence, consistent with the predictions of the CDPA model, high confidence "know" judgments were faster than high confidence "remember" judgments while having approximately the same old/new accuracy.

Additionally, the CDPA model also predicts that for responses made with low confidence, "know" judgments will be slower than "remember" judgments. Eight of the 31 participants made at least one low confidence "know" and low confidence

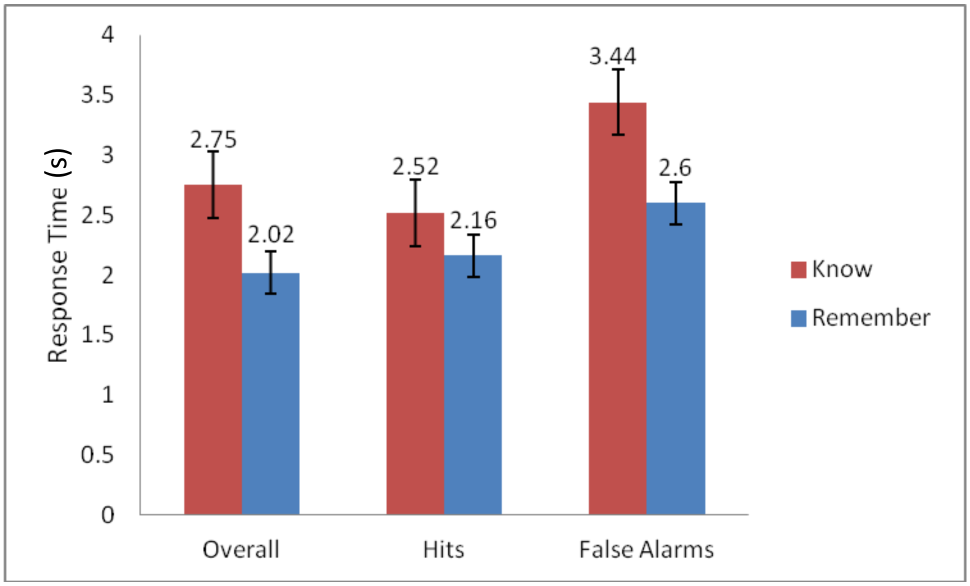

Figure 4.6. Mean response time for low confidence “know” and “remember” responses collapsed over targets and distracters (overall), to targets alone (hits) and to distracters alone (false alarms).

“remember” response. Data from these participants was analyzed. Figure 4.6 shows the mean response time for low confidence old “remember” and “know” responses collapsed over targets and distracters (overall), to targets alone (hits) and to distracters alone (false alarms). Response time for low confidence “know” judgments (2.75s, SD = .52) was significantly slower than response time for low confidence “remember” judgments (2.02s, S.D = .82), $t(7) = 2.9$, $p < .05$. Response time data was then analyzed separately for hits and false alarms. Low confidence “know” hits (2.52s, SD = .56) were significantly slower than low confidence “remember” hits (2.16s, S.D = .74), $t(6) = 2.52$, $p < .05$. Low confidence “know” false alarms (3.44s, SD = .59) were slower than low confidence “remember” false alarms (2.6s, S.D = 2.3), but the difference was not significant.

We further analyzed response time data for 7 of the 31 participants who made at least one response in all four relevant categories (high confidence remember, high

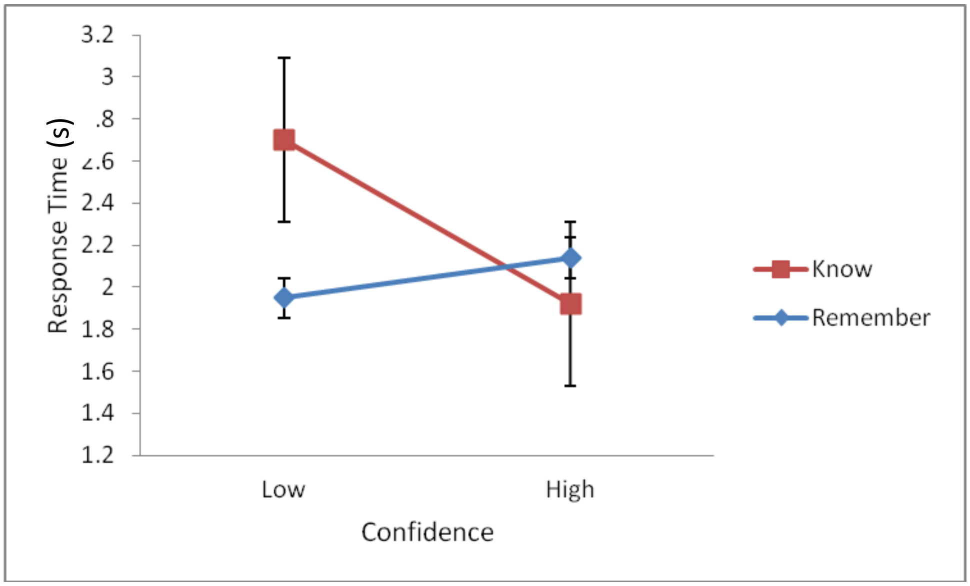

Figure 4.7. Interaction between response times for low versus high confidence "know" and "remember" judgments.

confidence know, low confidence remember and low confidence know). A 2x2 ANOVA was performed on the effect of confidence (low versus high) and judgment (remember versus know). If high confidence "know" judgments are faster than high confidence "remember" judgments while the opposite is true for low confidence responses, then the interaction between confidence and judgments should be significant. As shown in Figure 4.7, the interaction was indeed significant, $F(1,6) = 9.07$, $p < .05$.

A final prediction of the CDPA model is that response times will be more variable for high confidence "remember" judgments than for high confidence "know" judgments but that collapsed over confidence, response times will be less variable for "remember" judgments than for "know" judgments. The standard deviation of response times was greater for high confidence "remember" responses (1.23, S.D = 1.33) than for high confident "know" responses (.85, S.D = .51), while the standard deviation of response times collapsed over confidence was smaller for "remember" responses (1.32, S.D =

1.14) than for “know” responses (1.45, S.D = .96). However, in both cases, the difference was not significant.

4.3 Fitting the CDPA model to Empirical Data

The chi-square method was used for fitting the CDPA model to data. The empirical RT data for both hits and false alarms was divided into seven categories. These categories comprised of "old" judgments, divided into 6 groups on the basis of post-recognition judgment (remember and know) and confidence (low, medium or high), and "new" judgments. Within each category four bins (quartiles) were chosen, each containing 25% of the data. For each category, the RTs predicted by the model that divide the data into the four bins (within the category) were computed. The expected frequency (E) within each bin (for each category) was then 25% of the total number of responses predicted by the model in the category. Within each category, comparing the predicted quartile RTs with the observed data provided the observed frequency up to that quartile (for that category). Subtracting the frequency for each successive quartile from the next higher quartile within a category, determined the number of responses observed between each pair of quartiles, and hence the observed frequency in each bin of each category. The chi-square statistic minimized was,

$$\frac{(O-E)^2}{E}$$

summed over the 56 bins, 28 for hits and 28 for false alarms.

The best fitting parameters values for the free parameters are listed in Table 4.1. We assumed targets and distracters to have the same diffusion constant, and hence the same standard deviation. The bound B was set to 1.0. Four of the twelve parameters consisted of the locations of decision criteria (two confidence criteria, a remember

Table 4.1. *Best-Fitting Parameter Values for the CDPA model.*

Parameter	Description	Value
C_{High}	High confidence criterion	0.63
C_{Low}	Low confidence criterion	04769787
μ_F	Mean drift rate for familiarity process (Targets)	0.13935456
μ_R	Mean drift rate for recollection process (Targets)	0.00947192
D_F	Diffusion constant for familiarity	0.09416173
D_R	Diffusion constant for recollection	0.05391228
τ	Rate at which the bound collapses	0.28585528
B_r	Recollection criterion	0.35386679
z_0	Starting point	-0.09009103
μ_{F_0}	Mean drift rate for familiarity process (Distracters)	-0.10018318
μ_{R_0}	Mean drift rate for recollection process (Distracters)	-0.04959973
δ_T	Interval between old/new response and confidence judgment	0.43406613

criterion and starting point). The other parameters represented the distribution of the target and lure distribution for recollection and familiarity. Consistent with the fundamental assumption of the model, the estimated mean drift rate for familiarity was faster than for recollection.

The data and fits of the model to the data (Figure 4.8 and 4.9) are displayed in latency probability functions to show the relationship between response time and accuracy. For each category, response time is plotted against the probability of making a response (at that time). Figure 4.8 shows the overall (averaged over confidence) fit for both "old and "new" responses. The fit of the model matches the overall empirical latency probability functions, with an average chi-square of 5.33. However, the model is unsuccessful in making accurate predictions for the proportion of responses and their RTs when confidence is incorporated as a dependent measure. Figure 4.9 shows the predicted and empirical latency probability distributions for “remember” and “know” responses in

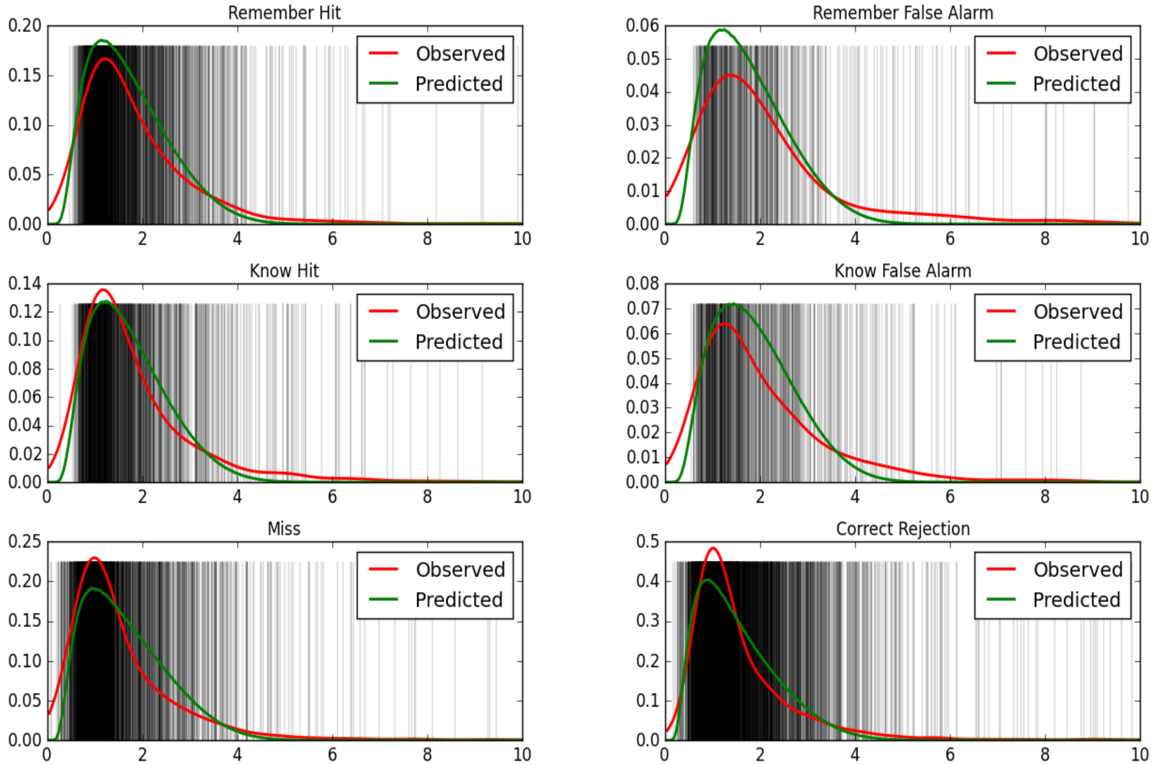

Figure 4.8. Predicted and observed latency probability functions for hits, false alarms, misses and correct rejections averaged over confidence. The x-axis represents the response time (in seconds) and the y-axis represents the probability of making a response.

each confidence category (low, medium and high), for hits and false alarms. A high average chi-square value of 167.31 corroborates the poor fit of the model.

As can be seen in Figure 4.9, the model provides a better fit for “know” responses (chi-square = 46), than for remember responses (chi-square = 117). One possible reason for this could be that in the current version of the model, the determination of a post response remember/know judgment is made on the basis of recollected information that has accumulated at the time of making an old/new response. However, in the experimental (word recognition) task, between the old/new decision and the remember/know response, a small amount of time elapses, during which some additional recollected information may accumulate. Taking this extra information into consideration

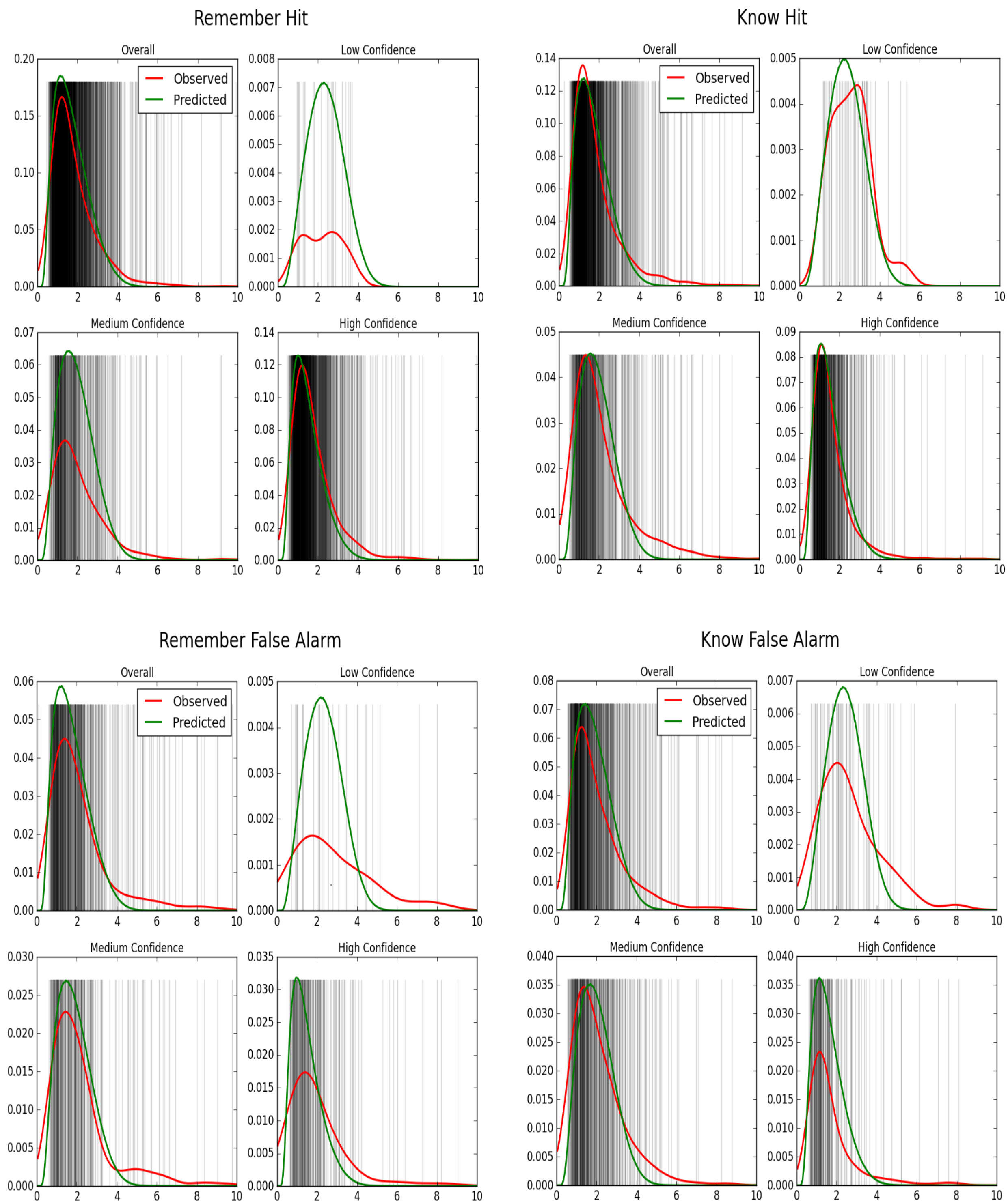

Figure 4.9. Predicted and observed latency probability distributions for remember and know hits and false alarms in each confidence category (low, medium, high).

when classifying "old" responses as "remember" or "know" could generate more precise predictions. This approach is discussed in more detail in Chapter 5 under future directions.

Additionally, the mean accumulation rate for recollected information is estimated by the model to be a great deal smaller than that for familiarity. It is therefore possible that old/new decisions are being made on the basis of familiarity alone, and most of remember responses are therefore post-response remember judgments. Additional experiments where participants are required to make a speeded remember/know/new response (instead of a speeded old/new response followed by a reflective remember/know response), need to be conducted to investigate this possibility.

Alternatively fitting the model over just accuracy and confidence without considering RT distributions (similar to the extant dual process models) generates accurate predictions for the proportion of remember and know responses in each confidence category, with an average chi-square value of 9.2. Hence, while the model proffers predictions that incorporate confidence, accuracy and RT, fitting to data across all three measures is non-trivial.

4.4 Discussion

The CDPA model assumes that recognition memory is supported by two distinct, continuous memory signals; familiarity, which consists of a memory signal associated with the item itself, and recollection, which consists of the retrieval of associated (contextual, source etc) information. Consistent with this, “remember” judgments were associated with significantly higher source accuracy than “know” judgments. Furthermore, consistent with the assumption that recollection and familiarity are continuous, both “remember” (based on recollection) and “know” (based on familiarity) responses were characterized by a positive correlation between confidence and old/new accuracy.

“Remember” judgments were made with higher confidence, higher old/new accuracy and were faster than “know” judgments. This common pattern is consistent with the CDPA model and most dual-process theories. However, unlike other dual process models, the CDPA model also predicts a mirror effect for “know” versus “remember” judgments, with fast high confidence “know” judgments faster than high confidence “remember” judgments and slow low confidence “know” judgments slower than low confidence “remember” judgments. Our findings confirm this prediction of the CDPA model. Hence, qualitatively the model is a good fit to the empirical data.

However, quantitatively the model falls short. Of course, while it does not provide the most precise fit to the data, it still offers reasonable predictions for accuracy, confidence and response time. Furthermore, computationally the model follows the experimental task very closely, which makes it flexible and adaptable to different experimental paradigms.

5. Conclusion

5.1 Implications

The concept of memory strength has a long and useful history both because it provides an intuitive interpretation of behavioral variables (namely, confidence and accuracy), that tend to covary and because it lends itself to more formal specification in terms of signal detection theory, which, in turn, helps to conceptualize a variety of memory related phenomena. However, its long-appreciated weakness is that any characterization of memory in terms of strength seems to deny the characterization of memory in terms of content, and it seems clear that memory, including recognition memory, is rich in content. These considerations have, in recent years, been particularly evident in the debate over the relative validity of the signal detection versus dual-process interpretations of recognition judgments. However, in this dissertation we demonstrate that these are not inherently incompatible points of view.

The CDPA model proposed here unites both dual-process theory and signal detection theories. Indeed, it extends signal detection theory to account for response time, and therefore makes it possible for the very first time to incorporate accuracy, confidence, and response time within a single recognition model. Another recent model to successfully combine the proportions of judgments in each confidence category and their RTs is the RTCON model (Ratcliff and Starns, 2009). Consistent with our assertion, Ratcliff and Starns (2009) also claim that analyses based on only one of the dependent variables are almost certainly wrong in the architectures of cognitive processes that they postulate. However, the RTCON model conceptualizes confidence in a fundamentally different way than the CDPA model. According to the RTCON model, the process that matches a test item against memory produces a normal distribution of memory evidence, and confidence criteria divide this distribution into areas, one for each confidence category. The area between the confidence criteria determines the accumulation rate for the corresponding confidence category. Since the accumulation rate determines RTs, the model therefore constrains response times by the same confidence criteria that determine confidence judgments, and is less flexible to the possibility (albeit small) of fast low confidence responses or slow high confidence responses. Additionally, RTCON is a single process model and does not take into account remember/know judgments. The CDPA model is therefore a significant advancement over current dual-process models that do not consider RT.

Furthermore, extending the dual-system hypothesis of memory to recognition judgments provides new insights on how familiarity and recollection information are retrieved over time. The identification of dual process models of human cognition with the dual-system theory of mammalian memory is an important theoretical development because it provides a well-established neurological basis for a dual process model and the description of the dual-system provides constraints on the possible features of the dual process model that may guide its feature development.

5.2 Future Directions

There are several possibilities that can be explored based on our work in this dissertation. Here, we list some of them and discuss ways to carry forward this work.

5.2.1 Computational Model

While the current version of the quantitative model provides a reasonable fit to the data, perhaps more precise predictions can be generated by considering the additional information that accumulates in between making an old/new response and a remember/know judgment (together with confidence rating).

If the old/new decision is made at time *T*, and a small time interval ∂_T elapses before the remember/know judgment is made, let us suppose that $R_{T+\delta_T}$ is the location of the recollected information and $X_{T+\delta_T}$ is the location of the total accumulated information at time $T+\partial_T$. The accumulated information can therefore be represented as a bivariate distribution, such that, one axis of the distribution corresponds to the recollected information (the criterion B_r is placed along this axis), and the other axis corresponds to the overall accumulated information (the confidence criteria are placed along this axis).

The proportion of remember (or know) responses, made with confidence C_i, at a given time *T* can then be obtained by determining what proportion of "old" responses (made at time *T*) fall into the relevant regions defined by the constant B_r and confidence bounds at time $T+\partial_T$. Hence, at time *T*, the proportion of remember responses made with confidence C_i is,

$$p_T\left(remember \mid C_i\right) = p_T\left(\text{old}\right)\int_{B_r}^{\infty}\int_{C_i}^{C_{i+1}} MVN\left(R_{T+\delta_T}, X_{T+\delta_T}\right) dR_{T+\delta_T}\, dX_{T+\delta_T},$$

where MVN stands for multivariate normal and represents the probability density function of a multivariate Gaussian distribution. The proportion of know responses made with confidence C_i is,

$$p_T\left(know \mid C_i\right) = p_T\left(\text{old}\right)\int_{-\infty}^{B_r}\int_{C_i}^{C_{i+1}} MVN\left(R_{T+\delta_T}, X_{T+\delta_T}\right) dR_{T+\delta_T}\, dX_{T+\delta_T}$$

Additionally, modifications can be made to the experimental design where participants are forced to make remember/know responses a fixed amount of time after making the old/new judgment. This would make δ_T a known value instead of a parameter that needs to be estimated.

5.2.2 Effects of Aging on Learning and Memory

Several studies have shown that aging results in a disproportionate impairment in free recall, whereas recognition memory is preserved (Schonfield and Robertson, 1966). However, since recollection is not only required for recall but also contributes to recognition, recognition should not be perfectly preserved when recall is impaired. Fitting the CDPA model to the accuracy and RT data from a word recognition task can determine how aging affects different components of the processing model. That is, whether the changes in the behavioral data result from changes in the old/new decision criteria, the non-decision components of processing, or the rates of accumulation of evidence from the stimuli. Functional brain imaging together with connectivity analysis using graphical causal modeling can also provide useful insights.

In particular, does the interaction between the hippocampus and caudate change in older adults? Do the two areas compensate for deficits in each other such that overall recognition judgments are unimpaired? A possible explanation could be that while the striatum declines with age, the medial temporal lobe is preserved. As a result, even though recollection is impaired, familiarity compensates for it and therefore overall recognition judgments are unaffected. To test this hypothesis, adults in different age groups can be compared on tasks involving associative learning and generalization. Older adults may have impaired associative learning consistent with age-related striatal declines while generalization may be spared due to relatively preserved hippocampal function with age. Such research has the potential to broaden our understanding of human learning and memory.

5.2.3 Model-Based fMRI Analysis

A critical assumption of the CDPA model is that two memory systems described by the dual-system hypothesis serve as the neural basis of the two processes (recollection and familiarity) involved in making a recognition judgment. While the fMRI data indirectly supports this assumption, a more convincing approach would be to regress predictions derived from the computational model against brain data, thereby showing which brain regions correlate significantly with the model predictions, and are thus most likely to implement the functionality of the model component.

In such an approach, the research question would be whether the model correctly predicts the results of an fMRI experiment, requiring the CDPA model to be consistent not only with available behavioral data but also with fMRI data. Equations of the model can be developed to generate predicted neural activation in the hippocampus and caudate (during every TR of the experiment) either for a same/different task or a conventional word recognition task. The predicted activation convolved with an HRF, produces the predicted BOLD response, which can be correlated with the observed data. Hence, model-based fMRI analysis can extend the CDPA to a neuro-cognitive model that can account for both behavioral and neurological data.

Furthermore, as discussed throughout this dissertation, the existing dual-process models postulate qualitatively different underlying processes might nevertheless give equally good accounts of recognition accuracy and confidence. Model-based fMRI can determine which of these competing models give the best account of fMRI data.

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Table 2.1. *Results and the predictions of various single and dual process models.*

		Dual process Models							Single process Models
		Segregated			Integrated				
		Serial		Parallel	Integrated-recognition, no post-recognition	Integrated-recognition, segregated post-recognition			
	Results	Atkinson Juola Model Atkinson and Juola (1974)	Yonelinas's Hybrid Model Yonelinas (1994)	Mandler Model Mandler (1980)	Single-decision-process model Kelley and Wixted (2001)	STREAK Rotello et al. (2004)	CDP Wixted and Mickes (2010)	CDPA	Donaldson Model Donaldson (1996)
1	Low-frequency words produce more hits and fewer false alarms than high-frequency words	✓	✓	✓	✓	✓	✓	✓	x
2	When word-pairs are studied, intact pairs can be discriminated from rearranged pairs in a recognition test.	✓	✓	✓	✓	✓	✓	✓	x
3	In a reversed-plurality task there are more know responses to similar lures and more remember responses to target items	✓	✓	✓	✓	✓	✓	✓	x

4	No difference in hit rate for low and high frequency words when recognition is performed under time pressure but false alarm rate unaffected	✓	✓	✓	✓	✓	✓	✓	x
5	Dividing attention during encoding (requiring subjects to conduct a concurrent task during study) reduces recollection but not familiarity	✓	✓	✓	✓	✓	✓	✓	x
6	Manipulations designed to increase the processing fluency of test items lead to an increase in familiarity-based recognition responses for both studied and non-studied items, while leaving recollection-based responses unaffected	✓	✓	✓	✓	✓	✓	✓	x
7	Changing the perceptual characteristics of a word between study and test (e.g., changing the presentation modality between visual and auditory modalities) leads to a decrease in	✓	✓	✓	✓	✓	✓	✓	x

	familiarity, but not recollection								
8	Across short-term delays (10 s or 8 to 32 intervening items) familiarity decreases rapidly while recollection is relatively unaffected	✓	✓	✓	✓	✓	✓	✓	x
9	Partial recollection of study item possible	x	✓	x	✓	✓	✓	✓	?
10	Confidence and accuracy for recognition judgments positively correlated	x	x	x	✓	✓	✓	✓	?
11	Recollection influences know judgments	x	x	x	✓	✓	✓	✓	?
12	Remember responses to targets faster than know responses to targets.	x	✓	x	✓	x	✓	✓	?
13	Remember responses to targets made with higher confidence than know responses	?	✓	?	✓	x	✓	✓	?
14	Remember false alarms on average made with higher confidence than know false alarms	?	✓	?	✓	x	✓	✓	?
15	Remember false alarms on average made with higher confidence than know hits	?	✓	?	✓	x	✓	✓	?

16	Remember false alarms faster than know false alarms	x	✓	?	✓	x	✓	✓	?
17	Remember false alarms faster than know hits	x	✓	?	✓	x	✓	✓	?
18	Know judgments can be given the highest possible confidence rating)	?	✓	?	x	✓	✓	✓	?
19	Overlap between confidence ratings for remember and know judgments	?	✓	?	x	✓	✓	✓	?
20	For equally high confident remember and know judgments, remember judgments associated with more recollected information	✓	✓	✓	x	✓	✓	✓	?
21	Mirror effect for know versus remember judgments, with high confidence know judgments faster than high confidence remember judgments and low confidence know judgments slower than low confidence remember judgments	✓	x	?	x	x	x	✓	?