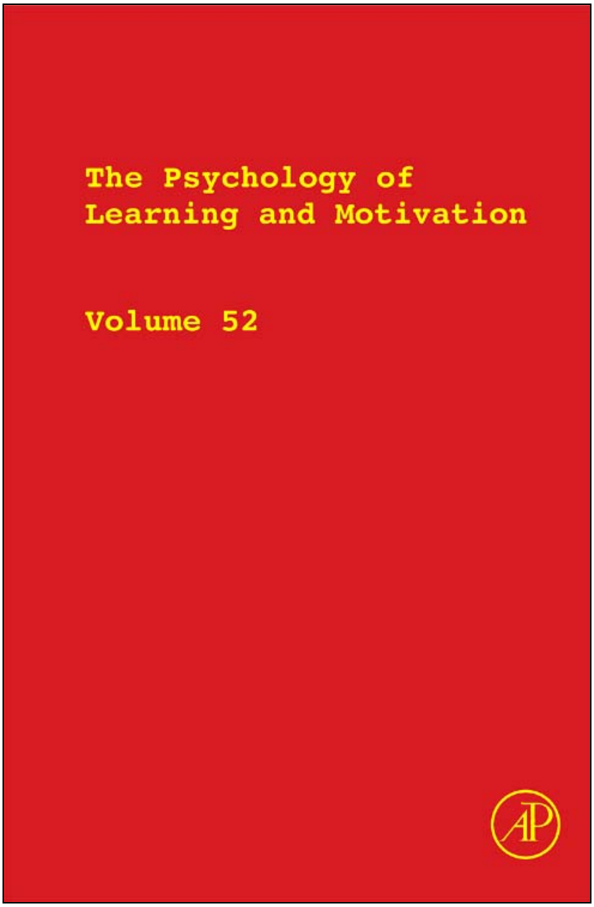

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CHAPTER FIVE

Defining and Investigating Automaticity in Reading Comprehension

Katherine A. Rawson

Contents

Abstract

In the literature on reading comprehension, automaticity has traditionally been defined in terms of properties of performance (e.g., speed, effort). Here, I advocate for a more powerful approach based on contemporary theories that conceptualize automaticity in terms of cognitive mechanisms that underlie practice effects on performance. To illustrate the utility of automaticity theories for understanding reading comprehension, the bulk of the chapter focuses on one particular kind of automaticity theory, which states that practice leads to

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decreasing involvement of algorithmic processing and increasing involvement of memory-based processing. I review evidence from recent studies specifically designed to diagnose memory-based automaticity in reading comprehension and findings from earlier studies that provide indirect evidence for this account. Finally, I consider directions for future research and theory development to address outstanding issues concerning the nature of automaticity in reading comprehension.

1. Introduction

Imagine if we all awoke one morning to find that we were no longer able to process written text—for most, the loss would mean professional paralysis, the entire public and private education system would come to a grinding halt, and many leisure and domestic activities could no longer be performed. Clearly, reading comprehension is an integral part of the lives of most individuals in a literate society. Ironically, most of us take reading comprehension for granted because of the speed, ease, and frequency with which we read, and outlandish thought experiments are needed for us to appreciate the importance of this sophisticated cognitive skill. However, anyone reading this chapter was once a beginning reader struggling to sound out or recognize words, who somehow through years of practice achieved the remarkable accomplishment of becoming a skilled reader for whom reading comprehension now seems largely automatic.

Two key questions arise from these observations: What does it mean to say that reading comprehension is automatic? And how does reading comprehension become automatic? Not only are these questions of basic theoretical interest, they also have important implications for the estimated 43% of adults in the U.S. who have only a basic or below-basic level of prose literacy (National Center for Education Statistics, 2006). Importantly, where we search for answers to the second question (how reading comprehension becomes automatic) depends critically on our answer to the first question (what automaticity is). Accordingly, Section 2 of this chapter considers how automaticity has traditionally been defined in the literature on reading comprehension and then advocates for a more useful approach to conceptualizing automaticity. Subsequent sections then focus on theories and empirical investigations of how reading comprehension becomes automatic. Section 3 describes evidence from current and past research, whereas Section 4 focuses on directions for future research and theory development to address outstanding issues concerning the nature of automaticity in reading comprehension. Finally, issues concerning the definition of automaticity are revisited in Section 5.

2. Defining Automaticity in Reading Comprehension

2.1. Property-List Accounts of Automaticity

Automaticity is a ubiquitous concept in the literature on reading comprehension. General models of comprehension often include assumptions concerning the automaticity of text processing (e.g., Kintsch, 1998; Perfetti, 1988). Similarly, theories of how specific component processes involved in reading comprehension operate (e.g., lexical processing, syntactic parsing, inferencing) also commonly include claims regarding the automaticity of these processes (e.g., Brown, Gore, & Carr, 2002; Flores d'Arcais, 1988; Greene, McKoon, & Ratcliff, 1992; McKoon & Ratcliff, 1992; Noveck & Posada, 2003). Automaticity also plays a prominent role in theoretical accounts of individual differences in comprehension skill within healthy adult populations (e.g., Walczyk, 2000) and those involving individuals with brain damage or disability (e.g., Kilborn & Friederici, 1994).

Because most people (researchers and laypersons alike) have an intuitive sense of what it means to say that something is automatic, it is perhaps not surprising that automaticity is not explicitly defined in much of the reading comprehension research in which the concept is invoked. When automaticity is defined, the virtually exclusive approach is to do so in terms of one or more properties of performance (i.e., *property-list* accounts of automaticity). These accounts generally accord with our intuitive sense of what automaticity refers to, such as "quick, easy, and outside of conscious awareness."

Intuition and convention notwithstanding, problems arise with this approach to defining automaticity. Both within and across areas of research in the reading comprehension literature, a persistent problem is inconsistency in the set of properties considered necessary and sufficient to define automaticity. Rawson (2004) provides more extensive discussion and illustration of this problem, so I only briefly summarize it here. In that study, I sampled 14 papers in which automaticity had been described in terms of properties. These property lists consisted of as few as two and as many as nine properties, and 14 different properties were invoked across lists. Most strikingly, no two property lists were the same, and the properties included on most lists (speed, resource dependence, obligatoriness, and openness to awareness) were explicitly excluded on at least one other list. Inconsistencies of this sort make it difficult to compare theoretical claims about the involvement of automatic processing in reading comprehension and may even give rise to spurious theoretical debates (e.g., for discussion of an extended but ultimately unresolved debate concerning automatic inference processes, see Rawson, 2004).

Even if agreement could be reached concerning necessary and sufficient properties, the larger problem with property-list accounts is that they are not explanatory. Delimiting the properties associated with nonautomatic versus automatic performance does not explain what underlies automatization or what gives rise to the properties of interest. For example, according to the compensatory-encoding model of individual differences in reading comprehension, less skilled readers ''possess subcomponents that are less automated'' (Walczyk, 2000, p. 560). In terms of the properties identified with automaticity in this model, the reading processes of less skilled readers presumably are slower, more effortful, require more attention, are more susceptible to strategic control, and are more selective, serial, flexible, error prone, and susceptible to interference. However, exhaustive documentation of these differences would still leave open the question of why less proficient versus more proficient readers differ in these ways and would be largely uninformative with respect to predicting what kind of training would most likely overcome these deficiencies.

2.2. Process-Based Theories of Automaticity

What then is the alternative to defining automaticity in terms of properties? Due in large part to limitations of the sort described above, contemporary theories from basic research on automaticity have turned instead to conceptualizing automaticity in terms of underlying cognitive mechanisms that give rise to properties of interest, rather than in terms of the properties themselves. These *process-based* theories are most concerned with explaining how the representations and processes that underlie task performance change with practice. Note the subtle but important shift in the nature of the question, from automaticity as an end state to *automatization* as a dynamic process and why properties of performance change as a result. In particular, the robust finding that practice yields a negatively accelerated speed-up in performance time is considered the signature pattern of automatization. Figure 1 depicts hypothetical response time curves to illustrate the qualitative pattern of speed-up with practice, and process-based theories are primarily focused on explaining this effect (to foreshadow, the three hypothetical conditions in Figure 1 are used to illustrate predictions of specific theories below).

To explain practice effects on the speed with which a task is performed, process-based theories have postulated several different cognitive mechanisms. A detailed and exhaustive review of these theories is beyond the scope of this chapter, so I limit discussion to a summary of the basic theoretical claims of each kind of theory. Given that the primary goal of this chapter is to illustrate how process-based theories can be used to further our understanding of automaticity in reading comprehension, the bulk of the chapter

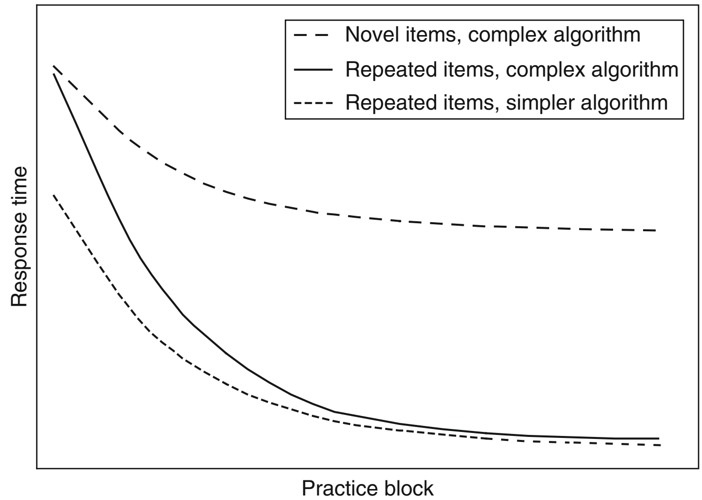

Figure 1 **Hypothetical pattern of response times illustrating the basic pattern of speed-ups with practice, as well as hypothetical differences in practice effects on response time as a function of kind of item and the complexity of the algorithm.**

will then focus on applying one of these process-based theories to investigate automaticity in reading comprehension.

2.2.1. Attention-Based Theories

The central claim of attention-based theories of automaticity is that performance becomes faster with practice due to changes in the amount or kind of information attended to during task performance. For example, a recent attention-based theory of automaticity is the *information reduction hypothesis* (Haider & Frensch, 1996, 1999). According to this account, with practice, individuals learn to focus attention on the most task-relevant information and to ignore irrelevant or redundant information. The reduction in the amount of information processed improves the speed of task performance. Several studies have reported results consistent with this theory (Haider & Frensch, 1996; Lee & Anderson, 2001; Schneider, Dumais, & Shiffrin, 1984; Schneider & Shiffrin, 1977). For example, Haider and Frensch presented letter strings containing a number that indicated how many letters were skipped in the sequence (e.g., A [3] E F G H, with 3 indicating that three letters were skipped between A and E). Participants had to indicate as quickly as possible whether the string preserved the consecutive order of letters in the alphabet. For incorrect strings, the error always involved the initial letter-digit-letter portion of the sequence, whereas the remaining letters were always correct (e.g., in A [3] F G H I, A [3] F is incorrect whereas G H I is correct). With practice, individuals learned to attend only to the initial letter-digit-letter triplet and to ignore the remaining letters.

The extent to which attentional shifts contribute to the automatization of reading comprehension is currently unknown. Intuitively, the contribution of these attention-based mechanisms in reading comprehension would seem minimal, given that most texts are unlikely to include information that is completely irrelevant to the topic or purposefully distracting. However, the finding in eye-tracking research that adult readers are more likely to skip over function words than content words (Rayner, 1998) might be taken as evidence for the plausibility of this mechanism during reading.

2.2.2. Algorithm Efficiency Theories

The central claim of algorithm efficiency theories is that practice improves the efficiency of the underlying algorithmic processes that compute interpretations of task stimuli, which in turn speeds task performance. Theorists have proposed several ways in which the efficiency of algorithmic processing may be improved, most notably in versions of ACT theory (e.g., Anderson, 1982, 1987, 1996; Anderson & Lebiere, 1998). Within ACT-R, an algorithm involves the execution of a sequence of *productions*, which function like ''if-then'' statements that indicate what action or transformation should occur given the current state of the system (e.g., ''IF goal is to find radius of circle and diameter is known, THEN divide diameter by two''). Algorithm efficiency may improve when two or more productions within a sequence are combined to reduce the overall number of computational steps that must be performed to complete the algorithm (Blessing & Anderson, 1996). Algorithm efficiency may also improve by tuning the strength of productions in procedural memory. The strength of a given production may be incremented when its execution leads to a correct result; likewise, the strength of a production may be decremented when its execution leads to an incorrect result. In this way, the strengthening process may increase the likelihood that effective productions are subsequently selected for execution and decrease the likelihood that ineffective productions are selected. ACT-R also assumes that the strength of a production influences how quickly it can be executed on subsequent processing trials.

Importantly, note that algorithms involved in computing interpretations of task stimuli are task-specific but item-general—that is, the algorithms can compute an interpretation for any token of a given stimulus type within a task domain, regardless of whether that token is familiar or novel. Thus, algorithm efficiency gains produce *item-general* practice effects, where the speed of processing improves across stimuli of a given type, even for particular stimuli that have not been practiced before (as depicted for the hypothetical novel item condition in Figure 1). Recent research has shown item-general effects of practice with linguistic units of various sorts, including syntactic structures and noun–noun conceptual combinations (e.g., Rawson, 2004; Rawson & Middleton, 2009; Rawson & Touron, 2009). This type of practice gain contrasts with *item-specific* practice effects (discussed further below), which are gains that are limited to specific stimuli that have been practiced before. These two effects are not mutually exclusive, in that both types of gain may be observed with practice of a given task.

2.2.3. Memory-Based Theories

The final class of process-based theories considered here are primarily intended to explain item-specific practice effects and are the focus of the remainder of this chapter. The central claim of memory-based theories of automaticity is that practice leads to a qualitative change in underlying processes, with a shift away from algorithmic interpretation of stimuli to retrieval of prior interpretations from memory. The progenitor of contemporary memory-based accounts is *instance theory* (Logan, 1988, 1992, 1995). According to instance theory, interpretation of a stimulus is based on algorithmic processing on the initial encounters of that stimulus, with each interpretation stored in long-term memory as a separate instance. Upon subsequent encounters of that stimulus, interpretation may be based either on algorithmic processing or on retrieval of a previously stored interpretation. The algorithm and retrieval routes are assumed to race in parallel, with interpretation based on the output of whichever route finishes first. Importantly, each instance is assumed to race against all other instances to be retrieved, with normally distributed finishing times for each instance. As the number of instances increases (through repeated encounters of specific stimuli), the likelihood that an instance is retrieved quickly enough to beat the algorithm also increases. Although the algorithm may still win the race on some proportion of trials, the main claim is that speed-ups with practice are due to increasing involvement of retrieval for repeated stimuli on later trials. For example, if you were asked to solve "$24 \times 7 = ?$," you would likely have to use multiplication rules to arrive at the solution. However, if repeatedly asked to solve this same problem, at some point you would presumably forego computation and instead simply retrieve the solution (168) directly from memory.

Two offspring of Logan's instance theory share the same core assumption that speed-ups with practice reflect shifts from algorithmic processing to retrieval, but they hold somewhat different representational and processing assumptions. The *component power laws theory* (or CMPL; Rickard, 1997, 1999, 2004) assumes that interpretations of a given stimulus are stored as a prototype (rather than as separate instances) that accrues strength in memory with increasing practice with that stimulus. CMPL also assumes that the algorithm and retrieval routes to interpretation do not run in parallel. Rather, only one of the two processes is initially engaged on any processing trial, and the other process is only executed if the initially selected process fails.

The other recent memory-based theory of automaticity is the *exemplar-based random walk theory* (or EBRW; Palmeri, 1997, 1999), which extends instance theory in several key ways. Palmeri notes that as originally proposed, instance theory is a pure instance model, in that the same stimulus must be presented to retrieve prior interpretations. In contrast, EBRW allows for retrieval of prior interpretations for stimuli that are similar to the current stimulus, and the speed with which instances are retrieved is a function of the similarity of those instances to the current stimulus. Given this assumption of similarity-based retrieval, a given stimulus may retrieve instances from more than one response category, thus introducing the potential for response competition. For example, encountering the letter string BUNT in a word identification task would presumably retrieve not only instances of "bunt" but also "bunk" and "runt." EBRW assumes that each retrieved instance directs a random walk toward a response threshold for the particular interpretation contained in that instance (and as result, away from the threshold for a competing response). Eventually, an interpretation for a stimulus is selected when the response threshold for one interpretation is reached. In contrast, instance theory assumes that the first instance retrieved determines the interpretation that is adopted on the current processing trial.

Which memory-based theory is best suited to explain automaticity in reading comprehension? Without further research, one can only speculate. However, EBRW may hold the most promise for two reasons. First, EBRW provides an important extension of the original instance theory by postulating how processing proceeds when different responses are possible for a given stimulus, which commonly occurs in reading comprehension. Whereas previous research on memory-based theories has typically involved unambiguous stimuli with only one possible response (e.g., in alphabet arithmetic, A + 2 always equals C), many of the units of information processed in reading comprehension permit more than one response. For example, the word "calf" may refer to a baby cow on some occasions but a leg muscle on other occasions. To the extent that prior interpretations of "calf" are retrieved during processing, some will include "baby cow" and others will include "leg muscle." EBRW postulates a random walk mechanism that would explain how competition between these two mutually exclusive meanings would be resolved (see Section 3.2.3).

Second, EBRW postulates that the algorithm and retrieval routes operate simultaneously, with interpretation based on the output of whichever process completes first. This assumption of parallel processing may be more reasonable for reading comprehension than CMPL's assumption that algorithm and retrieval cannot run simultaneously. Reading comprehension involves a complex system of cognitive processes that must operate in a coordinated fashion to interpret many different kinds of information (sounds, letters, words, concepts, propositions, syntax, etc.). Whereas some component processes are likely to heavily involve memory-based processing, other components will be restricted to algorithmic processing in most cases (see Section 4.1). If algorithm and retrieval processes cannot operate simultaneously, it is unclear how all of the various components involved in reading comprehension are able to contribute to the developing text representation in real time.

As mentioned earlier, the remainder of the chapter will focus on applying memory-based theories to understanding automaticity in reading comprehension. In the next section, I first discuss empirical evidence from recent studies that were specifically designed to demonstrate memory-based automatization in reading comprehension. I then discuss earlier studies that were not originally designed to explore memory-based automatization but nonetheless provide indirect evidence consistent with memory-based theories. To foreshadow, many of the findings discussed below are consistent with all three memory-based theories. In these cases, the theories will be discussed as a collective. For some findings, however, a greater degree of precision in explanation is desirable. In these cases, discussion will focus on EBRW in particular.

3. Investigating Automaticity in Reading Comprehension

Acquiring skill in reading comprehension takes years of practice and involves many small incremental improvements in the speed (and accuracy) of many different component processes. These incremental improvements likely involve several different mechanisms—indeed, the attention-based, algorithm efficiency, and memory-based theories described above are not mutually exclusive. However, the relative contributions of these mechanisms may differ widely as a function of task domain. Thus, positive evidence for memory-based automatization in other cognitive tasks does not guarantee its involvement in reading comprehension. What evidence exists for memory-based automatization in reading comprehension?

3.1. Direct Tests of Memory-Based Automaticity in Reading Comprehension

To investigate memory-based automatization in reading comprehension, we must first consider the two main empirical footprints of memory-based processing. The first concerns *algorithm complexity effects* (i.e., processing time differences due to more vs. less complex algorithmic processing) and how they change with practice. All three memory-based theories predict that algorithm complexity effects will be apparent at the beginning of practice with novel stimuli (i.e., when interpretation is based on algorithmic processing) but will diminish with repetition of those items (i.e., as interpretation is increasingly based on retrieval rather than the algorithm). The basic qualitative pattern is illustrated by comparing response times in the two hypothetical repeated conditions in Figure 1. For example, Palmeri (1997) reported patterns of this sort in a dot counting task. Participants were repeatedly presented arrays of 6–11 dots and were asked to report as quickly as possible how many dots each contained. At the beginning of practice, response times were longer for 11-dot arrays than for 6-dot arrays. Upon initial encounters of the arrays, individuals presumably used a counting algorithm to compute each response, and arrays requiring more counting took longer than arrays requiring less counting. However, by the end of practice, response times differed minimally as a function of numerosity. Presumably, individuals shifted to retrieving answers directly from long-term memory, and thus numerosity no longer mattered (for similar effects in alphabet arithmetic, see Klapp, Boches, Trabert, & Logan, 1991; Logan & Klapp, 1991).

Second, memory-based theories predict item-specific practice effects, in that speed-ups with practice due to shifting from algorithm to retrieval will be limited to repeated stimuli for which there are prior interpretations stored in memory. Among the memory-based theories, this prediction may be softened somewhat for EBRW, given that it allows for practice effects to accrue to new stimuli if they are sufficiently similar to repeated stimuli. Nonetheless, the general prediction is that speed-ups with practice should be greater for repeated stimuli than for novel stimuli of the same type. The basic qualitative pattern is illustrated by comparing response times in the two complex algorithm conditions in Figure 1. For example, Logan and Klapp (1991) reported faster response times for alphabet arithmetic equations that were repeated during training than for equations only presented once at the end of training.

Recent research has examined the extent to which the two empirical footprints of memory-based automatization—decreasing algorithm complexity effects and item-specific practice effects—can be observed during reading comprehension. Of course, reading comprehension is not a process but rather a system of coordinated processes. A nonexhaustive list of component processes involved in reading comprehension includes sublexical processes (e.g., phonological, orthographic, and morphological processing), lexical processes (e.g., word recognition, word meaning processes), supralexical processes (e.g., syntactic and thematic parsing processes that identify the grammatical and semantic relationships between words), and inferential processes (e.g., forward and backward causal inferences, elaborative inferences, pragmatic inferences). Thus, memory-based automatization must be investigated within a particular component process in the comprehension system. Below I describe studies of memory-based automatization in two different component processes.

3.1.1. Resolving Syntactic Ambiguity

Rawson (2004) presented readers with short narratives containing target sentences that were either syntactically ambiguous or unambiguous. For example, one story contained a sentence that began "The troops dropped...." The sentence is syntactically ambiguous at the verb "dropped," because more than one syntactic structure is possible at that point. The sentence could continue with "dropped" as the main verb (as in Sentence A) or as a constituent of a reduced relative clause (as in Sentence B); these cases are commonly referred to as *main verb/reduced relative (MV/RR) ambiguities*.

A. The troops dropped from the plane.
B. The troops dropped from the plane could overshoot the target.
C. The troops who were dropped from the plane could overshoot the target.

Previous research has established that readers typically resolve MV/RR ambiguities by assuming that the verb is the main verb of the sentence. However, the ambiguous target sentences in the Rawson (2004) materials instead disambiguated with a relative clause. Because readers initially compute a main-verb interpretation at the point of the ambiguous verb, upon subsequent encounter of the actual main verb in the *disambiguating region* (e.g., "could overshoot" in Sentence B), reanalysis is necessary to correct the initial misinterpretation. Reanalysis leads to an increase in reading times in the disambiguating region, relative to a control condition involving unambiguous versions of the target sentence, as in Sentence C. In this sentence, the role of "dropped" as part of a relative clause is explicitly indicated by "who were." Thus, initial interpretation is correct and no reanalysis is needed in the subsequent disambiguating region.

To illustrate how materials of this sort are useful for diagnosing memory-based automatization during reading, I briefly summarize methods and results from Experiment 4 of Rawson (2004). In the repeated condition, stories in which the target sentence was ambiguous (as in Sentence B) or unambiguous (as in Sentence C) were each presented eight times (see sample story in Table 1). In the unrepeated condition, stories containing an ambiguous target sentence were only presented once in Practice Block 2, 4, 6, or 8. The primary dependent variable was reading time in the disambiguating region.

To revisit, memory-based theories predict two basic patterns (illustrated in Figure 1), diminishing algorithm complexity effects and item-specific practice effects. Predictions concerning algorithm complexity effects involve the repeated ambiguous and repeated unambiguous conditions. On Trial 1, reading times in the disambiguating region ("could overshoot") will be longer in Sentence B than in Sentence C due to reanalysis of the initial misinterpretation of "dropped" as the main verb in Sentence B. The critical prediction concerns reading times at the end of practice. If readers shift to retrieval of prior interpretations, the correct interpretation of "dropped" will be retrieved in both conditions, avoiding the need for reanalysis in Sentence B by the end of practice. As shown in Figure 2, results confirmed the predicted pattern. Reading times in the disambiguating region on Trial 1 were significantly longer in the repeated ambiguous condition than in the repeated unambiguous condition, but reading times in the two conditions did not differ significantly by the end of practice.

Table 1 Sample Text From Rawson (2004).

Jones had been assigned to the press conference at the Capitol. Only recently hired by the paper, it was the most important assignment he had yet been given. Congress announced that the budget for the next fiscal year had been approved. Military officials (who were) delivered the reports *were unhappy* with the cuts. Jones thought that playing up the controversy might make for a better article.

Note: For illustrative purposes, the ambiguous verb is underlined and the disambiguating region is italicized (the phrase in parentheses was presented in the unambiguous version of the target sentence).

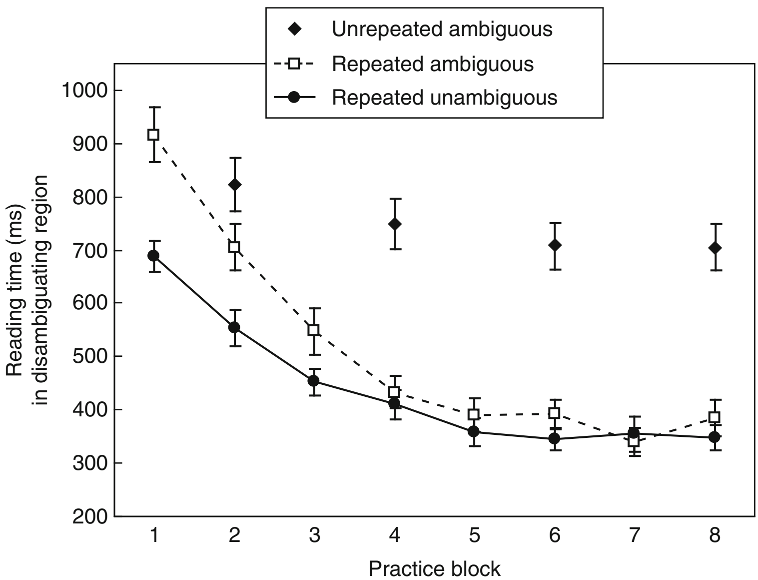

Figure 2 Mean reading time (ms) in the disambiguating region of syntactically ambiguous and unambiguous target sentences during practice, as a function of repetition and practice block. Error bars represent standard error of the mean (adapted from Figure 8 and Figure 9 in Rawson, 2004).

The prediction concerning item-specific practice effects involves the repeated ambiguous and unrepeated ambiguous conditions. As described above, by the end of practice in the repeated ambiguous condition, readers are presumably retrieving the correct interpretation of "dropped" and thus avoiding reanalysis in the disambiguating region. In contrast, reanalysis will be required for unrepeated ambiguous items throughout practice because initial misinterpretation of "dropped" cannot be avoided via retrieval of prior interpretations. Consistent with this prediction, reading times were significantly faster in the repeated ambiguous condition than in the unrepeated ambiguous condition throughout practice.

Using variations of the method described above, Rawson (2004) reported evidence from five experiments demonstrating retrieval of prior interpretations in syntactic parsing. However, this study represented the only direct test of memory-based theories of automaticity in reading comprehension, and several questions remained concerning the generality of memory-based automatization in reading comprehension. First, to what extent does memory-based automatization play a role in comprehension processes other than syntactic parsing? Second, does memory-based processing support interpretation when repeated items are transferred to new contexts? Third, do both practice effects and transfer effects obtain when repeated items are reencountered after a delay? Fourth, do the empirical footprints of memory-based automatization obtain with age groups other than young adult readers? In the next section, I summarize research providing answers to each of these questions.

3.1.2. Conceptual Combination

To extend to another component process, Rawson and Middleton (2009) examined the involvement of shifts from algorithm to retrieval during *conceptual combination*, one of the many semantic processes involved during reading comprehension. Conceptual combination refers to the combination of two or more concepts to elaborate characteristics of the base concept or to create a new concept. In English, conceptual combinations typically involve adjective-noun combinations (e.g., "prickly arguments") or noun–noun combinations (e.g., "banana fight"), both of which are quite common in natural language (see examples in Table 2).

Paralleling the syntactic ambiguity materials used by Rawson (2004), Rawson and Middleton developed novel noun–noun combinations (e.g., "bee spider") that afforded more than one possible interpretation. Several norming studies were conducted to establish the normatively preferred or *dominant* meaning of each combination, and then a plausible alternative or *subordinate* meaning was also selected. For example, without any disambiguating context, most individuals assume that "bee spider" refers to a spider that looks like a bee, whereas a plausible alternative meaning is a spider that eats bees. Each combination was then embedded in a short story containing

Table 2 Examples of Conceptual Combinations.

"Redsled, on the west slope of the divide, was fissured with thermal springs which attracted tourists, snowmobilers, skiers, hot and dusty ranch hands, banker bikers dropping fifty-dollar tips."
(Annie Proulx, *Close Range: Wyoming Stories*, p. 48)

"Basically, we're the bullet sponge."
(First Lt. Daniel Wright, executive officer of an American unit in Afghanistan, whose function is to draw insurgents away from more populated areas, creating security elsewhere, *New York Times*, 11/10/2008)

They play in cemeteries now, he thought, and tried to imagine a world where children had to play in cemeteries—death parks.
(Stanley Elkin, *The Living End,* p. 80)

"From attic trapdoors, blind robot faces peered down with faucet mouths gushing green chemical. . . But the fire was clever. It had sent flames outside the house, up through the attic to the pumps there. An explosion! The attic brain which directed the pumps was shattered into bronze shrapnel on the beams... The house shuddered, oak bone on bone. . ."
(Ray Bradbury, *The Martian Chronicles*, p. 254)

Note: Above are examples of conceptual combinations (underlined) from natural language samples and the literary contexts in which they appeared.

two critical sentences. The first sentence introduced the novel combination, and the second target sentence included a *disambiguating region* that stated the intended meaning of the combination (either the dominant meaning or the subordinate meaning; see the sample text at the top of Table 3).

Using these materials, Rawson and Middleton conducted three experiments involving various manipulations to further explore the generality of memory-based processing. Across experiments, several different findings converged to provide further evidence for memory-based automatization during reading comprehension. All of the important manipulations and critical effects reported across experiments by Rawson and Middleton (2009) were replicated in a recent unpublished study using their materials, which I summarize here to more concisely illustrate the key findings.

During the first session, stories containing either the dominant version or the subordinate version of the target disambiguating sentence were presented once in each of four blocks of practice (i.e., the *repeated dominant* and *repeated subordinate* conditions, respectively). Two days later, each of the repeated stories was presented four more times. In both practice sessions, stories containing subordinate target sentences were each presented only once at the beginning or end of practice (i.e., the *unrepeated subordinate* condition).

Table 3 Sample Materials From Rawson and Middleton (2009).

Professor Dennison consistently had a high level of enrollment in his physics course not only because he was a fabulous teacher but because he was a peculiar, funny sort of man, and the students loved him. His physics demonstrations were clever and entertaining. For example, once he plopped down cross-legged on a platform with wheels, firmly grasped a large fire extinguisher, and shot himself across the room with it to demonstrate principles of momentum and inertia. His other extremely entertaining feature was his wardrobe. One day he came to class in bunny slippers. On another occasion, he wore a beret to complement his garish zebra tie. It was a tie [*with black and white zebra stripes/with cartoon zebras on it*]. And, according to rumor, he never fails to don, for one day a year in late September, his authentic Bavarian lederhosen, which is his way of commemorating the German Oktoberfest. Without a doubt, Professor Dennison is an extremely free-spirited individual.
Target sentence used in transfer task: Jonathon put on his zebra tie in protest of the wedding his wife was dragging him to, but she was not amused by the tie [*with black and white zebra stripes/with cartoon zebras on it*].

Note: For illustrative purposes, the novel combination is underlined and the disambiguating region is italicized (the dominant version of the disambiguating region is the first phrase in the bracket and the subordinate version is the second phrase in the bracket).

Figure 3 reports reading times in the disambiguating region of target sentences in each condition during the two practice sessions. First, reading times were significantly longer for repeated subordinate items than for repeated dominant items on Trial 1 but then converged by Trial 8 (i.e., diminishing effects of algorithm complexity). Second, reading times in the disambiguating region were faster for repeated subordinate items than for unrepeated subordinate items (i.e., item-specific practice effects). These two findings parallel those reported by Rawson (2004), thus extending the evidence for memory-based automatization in to semantic processing.

Concerning the question of whether memory-based processing supports interpretation when repeated items are encountered in new contexts, a transfer task was administered in a third session 2 days after practice. To mask the real purpose of the transfer task, participants were given cover task instructions explaining that they would complete a series of measures of basic reading comprehension ability. One of the tasks was a sentence sensibility judgment task, in which participants read a list of sentences one at a time and were asked to indicate if each one was sensible or insensible. A minority of the sentences in the list were actually new sentence frames for the combinations that had been repeatedly presented in the stories during the practice sessions (see example transfer sentence in Table 3). Importantly,

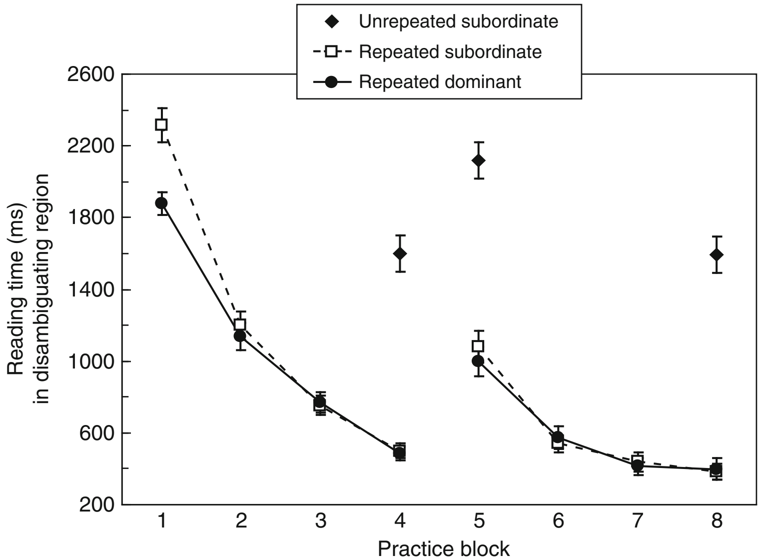

Figure 3 Mean reading time (ms) in the disambiguating region of target sentences during practice, as a function of the meaning of the conceptual combination and practice block. Error bars represent standard error of the mean.

in each sentence, the combination was followed by a disambiguating region that contained either the same meaning as during practice or the nonpracticed meaning.

Figure 4 reports reading times in the disambiguating region of target sentences in each condition of the transfer task. If encountering repeated items in a new context minimizes the involvement of memory-based processing, interpretation of the combinations in the transfer sentences would revert to algorithmic processing. Given that the algorithm is most likely to generate the dominant meaning of the combinations, one would predict only a main effect of transfer meaning, with reading times significantly faster in the dominant versus subordinate transfer sentences regardless of the meaning of the combinations during practice. In contrast, the observed crossover interaction implicates retrieval of prior interpretations. Consider the subordinate transfer condition. For items that had been practiced with their subordinate meaning, these stored interpretations were presumably retrieved upon encounter of the combination in the transfer sentence. When the subsequent disambiguating region contained the subordinate meaning, no reanalysis was required. In contrast, if the disambiguating region contained the dominant meaning, reanalysis would be needed and reading times would increase as a result. The same logic applies to the pattern in the dominant transfer condition.

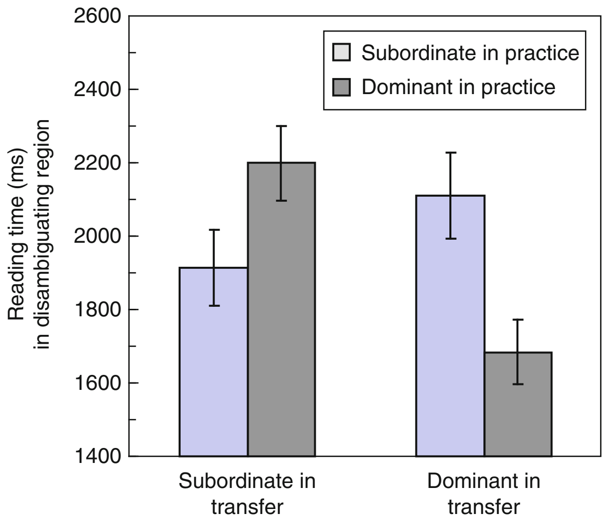

Figure 4 Mean reading time (ms) in the disambiguating region of target sentences during the transfer task, as a function of the meaning of the conceptual combination during practice and during transfer. Error bars represent standard error of the mean.

Concerning the question of memory-based processing across delays, note that both practice effects (Figure 3) and transfer effects (Figure 4) obtained across a delay. Regarding the transfer effects, 2 days separated the second practice session and the transfer task. Regarding the practice effects, 2 days separated Block 4 and Block 5 of practice. Although some loss occurred across the delay (reading times were significantly slower in Block 5 than in the Block 4), much of the speed-up gained in Session 1 was preserved across the delay (reading times were significantly faster in Block 5 than in Block 1). Additionally, reading times in Block 5 were still significantly faster for repeated subordinate items than for unrepeated subordinate items, suggesting interpretation of the repeated subordinate items was primarily based on retrieval of interpretations stored during Session 1. Thus, the key patterns implicating memory-based automatization obtained when items were reencountered after a delay.

Finally, concerning the question of whether evidence for memory-based automatization in reading comprehension obtains with age groups other than young adult readers, Rawson and Touron (2009) presented younger and older adult readers with stories similar to those developed by Rawson and Middleton (2009), containing a novel conceptual combination followed by a subsequent disambiguating sentence. Stories containing either the dominant version or the subordinate version of the disambiguating sentence were presented once in each of several blocks of practice (i.e., the *repeated dominant* and *repeated subordinate* conditions). Another set of stories containing subordinate disambiguating sentences were each presented only once at some point in practice (i.e., the *unrepeated subordinate* condition).

Both age groups showed the two empirical footprints of memory-based automatization: Reading times in the disambiguating region were significantly longer for repeated subordinate items than for repeated dominant items at the beginning of practice but then converged by the end of practice (i.e., diminishing effects of algorithm complexity), and reading times were faster for repeated subordinate items than for unrepeated subordinate items (i.e., item-specific practice effects). The primary age difference was that older adults required more trials of practice to shift to retrieval of prior interpretations. Interestingly, a second experiment indicated that older adults' slower shift was not due to memory deficits but rather to some reluctance to rely on retrieval. Most important, the results across both experiments provided initial evidence that older adults also exhibit memory-based automatization during reading comprehension.

In all of the studies discussed to this point, the primary dependent variable was reading times in the disambiguating region of target sentences, because memory-based theories make *a priori* predictions for how reading times in this region should change as a function of practice. In contrast, the memory-based theories do not make strong *a priori* predictions for the pattern of reading times in the region of the sentence that contains the conceptual combination (e.g., the underlined portion of the sentence, ''With its advanced technology, *the cheetah bike was the most impressive* of all the toys'').[1] Nonetheless, *post hoc* analyses of reading times in this region revealed a relatively consistent and informative pattern of results across several experiments.

Specifically, for each participant in each practice block, mean reading time for the combination region in the repeated dominant condition was subtracted from mean reading time for the combination region in the repeated subordinate condition. The mean difference across participants in each practice block is reported in Figure 5; given the exploratory nature of these analyses, results are reported from eight different experiments. Although the magnitudes of the effects differ somewhat across experiments, all data sets show the same basic pattern. First, on Trial 1, the difference in reading times between the repeated dominant and repeated subordinate conditions was not significant. The memory-based processing theories assume that the first time a to-be-repeated combination is encountered, no prior interpretations are available to be retrieved and thus an

[1] During the experiments, the region containing the combination ('the cheetah bike') and the spillover region ('was the most impressive') were presented separately. However, the effects described below tended to manifest in both regions, so I report analyses in which reading times are collapsed across these two regions for sake of simplicity.

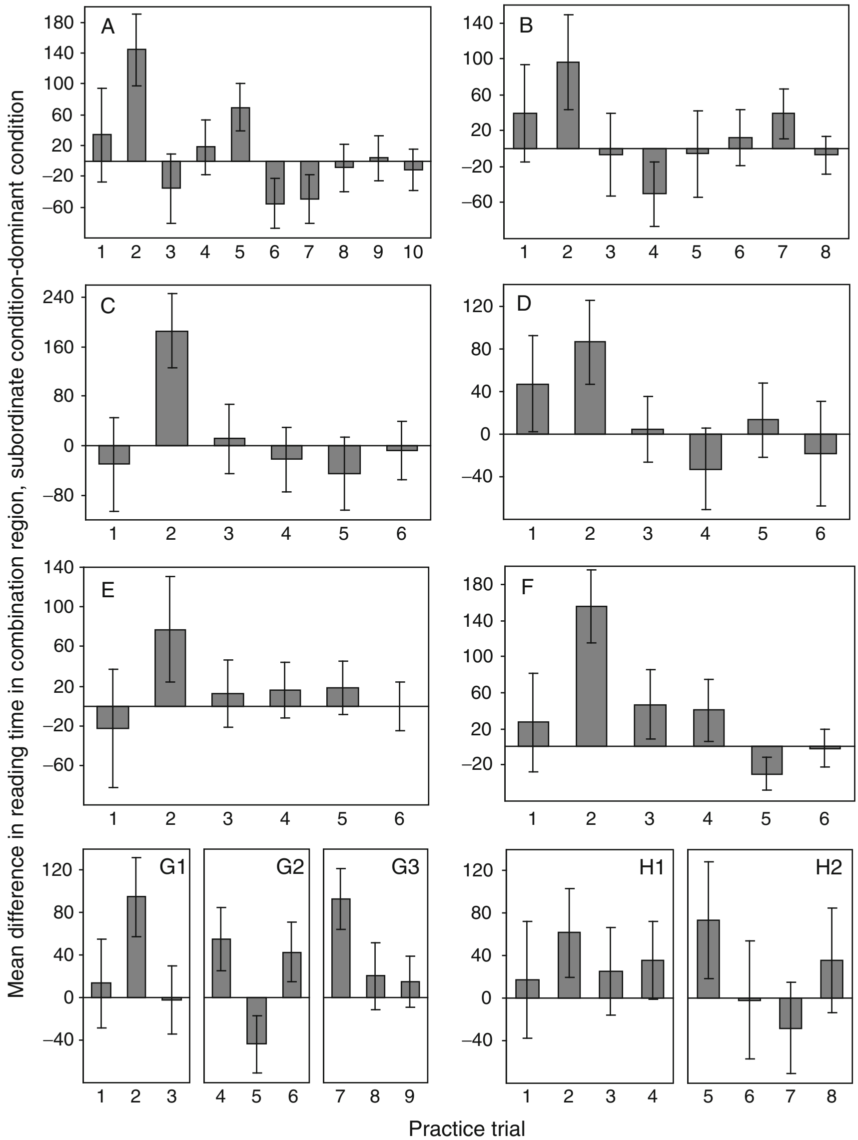

Figure 5 Mean difference in reading time (ms) in the region of the sentence containing the conceptual combination in the subordinate versus dominant condition (positive values indicate longer reading times in the subordinate condition). Error bars represent standard error of the mean. Values along *x*-axes indicate practice trial. Panels A and B report data from Rawson and Touron (2009), Experiments 1 and 2. Panels C and D report unpublished data. Panels E and F report data from Rawson and Middleton (2009), Experiments 1 and 2. Panels G1–G3 report data from Sessions 1–3 of Rawson and Middleton (2009), Experiment 3. Panels H1 and H2 report data from Sessions 1 and 2 in the unpublished study described in Section 3.1.2.

interpretation must be computed. All combinations are likely to be initially interpreted with the dominant meaning, and thus no difference in reading times in the two conditions would be expected on the first trial.

However, on Trial 2, reading times in the combination region were significantly greater in the repeated subordinate condition than in the repeated dominant condition in all eight experiments. How might the memory-based theories explain this finding? One possibility is that the elevated reading time in the subordinate condition on Trial 2 reflects competition between the algorithm and retrieval routes. On Trial 2, the correct interpretation stored on the previous trial is now available to be retrieved. If the algorithm and retrieval routes operate in parallel, the two processes may output an interpretation at about the same time, because retrieval is still relatively slow early in practice. In the repeated dominant condition, both algorithm and retrieval would arrive at the dominant meaning. In contrast, in the repeated subordinate condition, computation would generate the dominant meaning but retrieval would produce the subordinate meaning. The elevated reading time in the repeated subordinate condition thus may reflect some form of interference between the two competing interpretations.

Competition between the two routes also provides a plausible explanation of the pattern of reading times later in practice. In contrast to the significant difference in reading times on Trial 2, differences in reading times on subsequent trials within an initial practice session (Panels A–F, G1, and H1 in Figure 5) tended to be minimal in all experiments. According to instance theory and EBRW, as the number of stored interpretations increases across subsequent trials, retrieval speed continues to improve. As a result, retrieval is increasingly likely to output an interpretation prior to the completion of the algorithm, avoiding interference.

Finally, consider the pattern of reading times in later sessions of practice that took place after a delay from an initial practice session (Panels G2, G3, and H2 in Figure 5). On the first trial in each of these sessions, reading times were again elevated in the subordinate condition. This pattern also follows from the rationale above. If some forgetting occurs over the delay between sessions, retrieval will be slower at the outset of the next session. Thus, algorithm and retrieval are once again more likely to output an interpretation concurrently, which would result in some interference in the subordinate condition.

Thus, the idea of competition between the algorithm and retrieval routes provides a plausible account of the pattern of reading times across trials and across sessions. Note that this account assumes that the algorithm and retrieval routes were operating concurrently in order for their outputs to have interfered with one another. Accordingly, this explanation is only afforded by instance theory and EBRW, given that CMPL assumes that the algorithm and retrieval routes do not run in parallel. However, neither EBRW nor instance theory explicitly describes how outputs from the two processes might interact with one another, and thus their account of the pattern of interference observed here would still be somewhat incomplete.

An alternative to the idea of competition between the two routes is that the elevated reading time on Trial 2 in the subordinate condition reflects competition within the retrieval route only. To revisit, all theories assume that the first time an item is encountered, interpretation is based on algorithmic processing. Thus, on Trial 1, combinations are presumably interpreted initially with the dominant meaning. Although subsequent disambiguating information corrects this initial misinterpretation in the subordinate condition, the initial dominant interpretation, although ultimately incorrect, may nonetheless persist in memory. In other words, the possibility is that two instances are stored for the combination: the interpretation from initial processing of the combination and the interpretation from reanalysis in the disambiguating region. This possibility is consistent with findings from research on syntactic parsing, showing that initial incorrect interpretations of syntactic ambiguities persist in memory in addition to the final correct syntactic interpretation that is stored after reanalysis (Christianson, Hollingworth, Halliwell, & Ferreira, 2001; Ferreira, Christianson, & Hollingworth, 2001).

If so, on Trial 2, both the initial dominant interpretation and the ultimate subordinate interpretation stored on Trial 1 would be available for retrieval. Neither instance theory nor CMPL currently includes assumptions that would allow for competition between interpretations during retrieval. In contrast, EBRW assumes iterative retrieval of instances, with each retrieved instance directing a random walk toward the particular interpretation contained in that instance until one response threshold is reached. On Trial 2 in the subordinate condition, extra retrieval steps would be needed to reach threshold because of the competing interpretations. Assuming that the subordinate meaning was more likely to ultimately win the retrieval competition (as suggested by the pattern of reading times in the subsequent disambiguating region described earlier), an increasing number of subordinate interpretations would be encoded. As a result, the dominant interpretation would be less competitive with increasing practice, which would explain the minimal elevation of reading times in the subordinate condition on later trials.

The one finding that poses difficulty for this account concerns the reemergence of elevated reading times in the subordinate condition on the first trial of later practice sessions. To explain this pattern, one would need to assume that the instances containing subordinate interpretations were more prone to forgetting than the instance containing the dominant interpretation, which would functionally increase the competitiveness of the dominant instance. On one hand, if primacy effects obtain in retrieval of this sort, they would favor the dominant instance. On the other hand, they would likely be offset by frequency and recency effects that would favor the subordinate interpretation. Thus, this retrieval competition account does not provide a straightforward explanation for the reemerging elevation of subordinate reading times in later sessions. Regardless of whether the dual-route competition account or the retrieval competition account is considered more viable, EBRW is the best equipped of the memory-based automaticity theories to accommodate both of these possibilities.

The preceding discussion highlights how consideration of automaticity theories in reading comprehension will advance our understanding of both. Automaticity theories provide relatively detailed explanations of how processing during reading comprehension can change with practice. In turn, the testing of automaticity theories in reading comprehension provides rich data sets that can constrain those theories. Extending automaticity theories to reading comprehension also reveals how the assumptions of these theories will need to be expanded to accommodate more complex tasks with less discrete stimuli than have previously been examined in prior automaticity research (a point that will be revisited in Section 4.3).

3.2. Indirect Evidence for Memory-Based Automaticity in Reading Comprehension

Taken together, findings from the studies described above provide foundational evidence for memory-based automatization of reading comprehension processes. Memory-based theories of automaticity—EBRW in particular—accrue further support to the extent that they provide plausible explanations for many empirical findings that have been reported in previous research. I discuss several illustrative examples below.

3.2.1. Verb Bias Effects

Another kind of syntactic ambiguity that is common in English concerns the case in which a noun phrase following a verb could be either the direct object of that verb (as in Sentence D) or the subject of a sentence complement (as in Sentence E), commonly referred to as *DO/SC ambiguities*. If readers initially assume "the valuable book" is a direct object in Sentence E, reanalysis will be necessary upon reaching the disambiguating region ("had been stolen"). As a result, reading times in this region would be longer in Sentence E than in its unambiguous counterpart, Sentence F, in which the syntactic role of "the valuable book" is explicitly signaled by "that." Across all DO/SC ambiguities in English, verbs are more likely to be followed by a direct object than by a sentence complement. However, individual verbs differ in the likelihood of being followed by a direct object versus a sentence complement (referred to as *verb bias*). For example, "read" is more likely to be followed by a direct object, whereas "believed" is more likely to be followed by a sentence complement. To what extent does this verb-specific information factor into readers' initial parsing of DO/SC ambiguities?

D. The librarian read the valuable book.
E. The librarian read the valuable book had been stolen from the archives.
F. The librarian read that the valuable book had been stolen from the archives.
G. The librarian believed the valuable book had been stolen from the archives.
H. The librarian believed that the valuable book had been stolen from the archives.

Trueswell, Tanenhaus, and Kello (1993) presented readers with ambiguous and unambiguous versions of sentences containing a sentence complement. Importantly, the main verb in each sentence was either DO-biased or SC-biased. For sentences with DO-biased verbs, reading times in the disambiguating region were significantly longer in the ambiguous condition (Sentence E) than in the unambiguous condition (Sentence F). In contrast, for sentences with SC-biased verbs, reading time differences were minimal (Sentences G and H). Findings across three experiments converged on the conclusion that "subcategorization information is accessed as soon as a verb is encountered, and it has immediate effects on the processing of information that follows the verb" (p. 548).

More recently, work by Hare, McRae, and Elman (2003, 2004) has suggested even finer-grained item specificity in verb bias effects. Hare et al. noted that many verbs have more than one sense (referred to as *polysemy*). For example, "found" can refer to the locating of some entity ("He found the baseball") or to achieving some realization or understanding ("He found that his watch had stopped"). Results of corpus analyses and norming studies revealed sense-specific biases for polysemous verbs (Hare et al., 2003). For example, for contexts in which "found" meant locating, it was more likely to be followed by a direct object than by a sentence complement (i.e., the "locating" sense of "found" is DO-biased). In contrast, for contexts in which "found" meant realizing, it was more likely to be followed by a sentence complement than by a direct object (i.e., the "realizing" sense of "found" is SC-biased).

Hare et al. then proceeded to embed the polysemous verbs in contexts that were semantically more consistent with one sense than the other. For example, the context in Item I favors the sense of "admit" that refers to confessing or conceding (which is SC-biased), whereas the context in Item J favors the sense that refers to permitting entry (which is DO-biased). In all cases, the target sentences contained a sentence complement that was unambiguously marked with "that" on half of the trials.

I. For over a week, the trail guide had been denying any problems with the two high-school kids walking the entire Appalachian Trail. Finally, he admitted (that) the students had little chance of succeeding.

J. The two freshman on the waiting list refused to leave the professor's office until he let them into his class. Finally, he admitted (that) the students had little chance of getting into the course.

Hare et al. found that reading times in the disambiguating region (e.g., "had little chance") were significantly longer in the ambiguous condition than in the unambiguous condition when the preceding semantic context supported the sense of the verb that was DO-biased (Item J) but not when the preceding context supported the SC-biased sense (Item I). In subsequent work, Hare et al. (2004) performed detailed analyses of materials used in earlier verb bias studies that had reported conflicting results and found that differences in the sense-specific biases of the polysemous verbs that had been used reconciled much of the apparent inconsistency.

In the terminology of automaticity theories, the interpretation of DO/SC ambiguities may be accomplished by item-general algorithmic processing or by item-specific memory-based processing. To the extent that interpretation is driven by algorithmic processing, DO/SC ambiguities would be resolved initially in favor of the direct object structure, regardless of the particular verb used in the sentence. However, the item-specific effects reported by Trueswell et al. (1993) implicate retrieval of specific information from prior encounters of particular verbs. Furthermore, the sense-specific effects reported by Hare et al. (2003) suggest that retrieval of information from prior encounters may be guided by semantic overlap between the current context and the previous contexts in which those verbs were encountered. This possibility is most easily conceptualized in terms of EBRW. Assuming that each prior instance contains information about the meaning of the verb as well as the syntactic frame in which it participated on that encounter (an assumption that will be revisited in Section 4.3.2), those instances with greater similarity to the current stimulus (i.e., those that share the same meaning of the verb in the current context) would be retrieved more quickly and thus would direct the random walk toward the threshold for the particular syntactic frame those instances contain.

3.2.2. Object-Relative and Subject-Relative Clauses

The syntactic parsing research discussed thus far has concerned the potential role of memory-based processing in resolving syntactic ambiguities. What role might memory-based processing play in the interpretation of unambiguous structures? In psycholinguistic research, among the most widely studied unambiguous structures include sentences containing object-relative clauses ("that the secretary disliked" in Sentence K) or subject-relative clauses ("that disliked the secretary" in Sentence L). Research has shown that readers generally have greater difficulty interpreting object-relative (OR) clauses than subject-relative (SR) clauses (e.g., King & Just, 1991;

Traxler, Morris, & Seely, 2002). Theoretical explanations for the increased difficulty of interpreting OR clauses commonly appeal to the notion of greater demands on working memory, either because more constituents must be maintained before syntactic assignments can be made or because of interference between the two noun phrases that must be maintained simultaneously (for a summary of these theories, see Reali & Christiansen, 2007a).

K. The accountant that the secretary disliked lost some important files.
L. The accountant that disliked the secretary lost some important files.

Almost all research on OR/SR clauses has used sentences such as the examples above, in which the relative clause contained a common noun (secretary) rather than a proper name ("that Sally disliked") or a pronoun ("that you disliked"). However, recent research has suggested that the increased difficulty of parsing OR clauses versus SR clauses may in part be due to differences in the frequencies with which OR versus SR clauses containing common nouns are encountered in the language. Reali and Christiansen (2007a) conducted corpus analyses revealing that 66% of OR clauses contained pronouns, whereas only 35% of SR clauses contained pronouns. Furthermore, OR clauses were much more likely than SR clauses to contain first-, second-, or third-person personal pronouns (e.g., I, you, she, they), whereas SR clauses were much more likely than OR clauses to contain third-person impersonal or nominal pronouns (e.g., it, someone).

In subsequent experiments, Reali and Christiansen (2007a) presented readers with sentences containing either an OR clause or an SR clause for self-paced reading. Importantly, the target clauses either contained a first-person pronoun, a second-person pronoun, a third-person personal pronoun, or a third-person impersonal pronoun (in Experiments 1–4, respectively). In contrast to the normative pattern of longer reading times for OR clauses than for SR clauses, reading times were faster for OR clauses than for SR clauses when they contained a first-, second-, or third-person personal pronoun. Reading times were only longer for OR versus SR clauses when they contained a third-person impersonal pronoun, consistent with the pattern of co-occurrences in the corpus analyses.

Reali and Christiansen (2007a) suggested that these biases may reflect the encoding of "schematized relative clause representations formed by sequential material with shared parts, such as *(Relativizer) I VERB*" (p. 19), as a result of frequent encounters of OR clauses containing pronouns. Memory-based theories of automaticity would suggest an even finer-grained unit of encoding may be at work here (a possibility also acknowledged by Reali and Christiansen, in addition to the more abstract OR clause template suggested). In terms of EBRW, each time a relative clause is encountered, the interpretation of that clause is stored as an instance. Presumably, the instance contains the specific words in the clause along with their syntactic and thematic role assignments on that particular encounter. If that particular sequence of words is encountered again, interpretation may be based on retrieval of the prior interpretation for that specific sequence, rather than on algorithmic processing at a more abstract or item-general level.

Of course, for this account to be viable, readers would need to have encountered the specific word sequences contained in OR clauses enough times for retrieval to be fast and reliable enough to beat the algorithm. On the face of it, this assumption might seem tenuous. However, an informal analysis of the materials used by Reali and Christiansen (2007a) suggests that the specific word sequences contained in OR clauses may be encountered more frequently than might be assumed on intuition alone. Table 4 reports the mean (and range) of page counts in Google[2] across the OR and SR clauses used in the target sentences for each of Reali and Christiansen's experiments. For example, the clause ‘‘that you visited’’ appeared on 133,000 Google pages; the average page count across all OR clauses used in Experiment 1 was 49,622. Likewise, ‘‘that visited you’’ appeared on 1060 Google pages; the average page count across all SR clauses used in Experiment 1 was 1813. Although Reali and Christiansen's clauses all began with ‘‘that,’’ I also included Google counts for clauses beginning with ‘‘who’’ and ‘‘whom,’’ given that EBRW allows for retrieval of highly similar instances. Consistent with Reali and Christiansen's finding that reading times were faster for OR clauses than for SR clauses when they contained a first-, second-, or third-person personal pronoun, Google counts for the particular tokens used in the materials for Experiments 1–3 were greater for the OR clauses than for the SR clauses. Also consistent with the finding that reading times were longer for OR clauses than for SR clauses when they contained a third-person impersonal pronoun, Google counts were lower for the OR clause tokens than for the SR clause tokens used in Experiment 4.

Obviously, the average adult reader has experienced much less language input than is accessible via Google. Is it plausible that Reali and Christiansen's participants could have acquired enough stored instances of these specific phrases from lifetime language exposure for memory-based processing of these items to manifest during the experiment? Assume that a typical undergraduate research participant has experienced 15 years of reading (including magazines, newspapers, books, letters, etc.) for 1 hour a day at an average reading rate across years of 200 words per minute, and 20 years encoding spoken language (including conversation, television, radio, music, etc.) for 3 hours a day at 150 words per minute. Based on these estimates, an average college student has processed more than 260 million words of input.

[2] Keller and Lapata (2003) demonstrated high correlations between page counts for bigrams in Google and frequency counts from standard corpus analyses.

Table 4 Mean Counts in Google for Object-Relative and Subject-Relative Clauses in Target Sentences used by Reali and Christiansen (2007a).

	OR clause	SR clause
Experiment 1		
That you visited/ visited you[a]	49,622 (102–213,000)	1813 (33–9700)
Who you visited/ visited you	9167 (2–44,300)	16,194 (82–139,000)
Whom you visited/ visited you	14,038 (8–105,000)	81 (0–348)
Total	72,827 (112–306,300)	18,088 (115–149,048)
Experiment 2		
That I hated/hated me	1,041,705 (525–10,900,000)	7866 (107–38,200)
Who I hated/hated me	85,931 (2–876,000)	54,755 (905–386,000)
Whom I hated/hated me	40,718 (312–234,000)	222 (6–1050)
Total	1,168,353 (2414–11,864,100)	62,842 (1583–425,250)
Experiment 3		
That they liked/liked them	84,460 (606–541,000)	5245 (7–35,300)
Who they liked/ liked them	4024 (5–24,800)	19,743 (209–124,000)
Whom they liked/ liked them	28,932 (10–338,000)	78 (0–696)
Total	117,416 (621–903,800)	25,067 (216–159,996)
Experiment 4		
That it followed/ followed it	145,630 (621–891,000)	151,452 (138–833,000)
Who it followed/ followed it	997 (0–13,000)	118,162 (164–749,000)
Whom it followed/ followed it	643 (0–3030)	197 (0–1680)
Total	147,271 (485–907,030)	269,811 (361–1,317,259)

[a] Values for one item removed as outliers.
Note: Values in parentheses report range of counts contributing to each mean. Google counts were performed in June, 2009.

Comparing the number of page counts in Google to frequency counts in British National Corpus (2007) (which contains about 100 million words from spoken and written language) for the 48 constituent words used in the target clauses (you, I, me, they, them, it, that, who, whom, and the 39 verbs) suggests about a 3900:1 ratio between the number of times an item occurs in Google versus in a 260-million-word corpus. If so, scaling down the "total" values reported in Table 4 would suggest that the typical undergraduate research participant had encountered the particular pronoun + verb OR clauses used in Experiments 1–3 an average of 116 times. By comparison, the research described in Section 3.1 showed that readers shifted from algorithm to retrieval-based interpretation after only 2–7 encounters of ambiguous verbs or conceptual combinations.

Consistent with this analysis, Reali and Christiansen (2007b) constructed sentences that were all of the same OR-clause type (pronoun + verb) that contained either a high-frequency phrase token ("I met" in Sentence M) or a low-frequency phrase token ("I distrusted" in Sentence N), based on Google counts. When sentences were presented in a difficulty rating task, sentences with high-frequency tokens were rated as less difficult than those with low-frequency tokens. Note that because the two sentences contain the exact same words, the difference in difficulty is most reasonably attributed to the phrases in which the words occur. Similarly, when sentences were presented for self-paced reading, reading times were faster for sentences with high-frequency tokens than for those with low-frequency tokens. Across sentences, regression analyses further revealed that as the difference in the frequency of the two tokens increased, the difference in reading times for the two versions of the sentence increased.

M. The attorney who I met distrusted the detective who sent a letter on Monday.

N. The attorney who I distrusted met the detective who sent a letter on Monday.

As Reali and Christiansen noted, "Distributional properties of language are often described without considering the differences between type and token frequencies" (p. 168). Consistent with memory-based theories of automaticity, their results clearly indicate that token frequencies in the language are predictive of reading performance.

3.2.3. Resolving Lexical Ambiguity

As Duffy, Morris, and Rayner (1988) summarized, "Research on lexical ambiguity has focused on two general questions. First, what meaning or meanings are retrieved during the initial lexical access process for ambiguous words? Second, what effect does preceding sentence context have on the access process?" (p. 429). To address these questions, Duffy et al. developed sentences that each contained two clauses. One clause contained either a target word with more than one meaning (e.g., "pitcher" can refer to a container for liquids or to a baseball player) or a matched control word with only one meaning ("whiskey"). The other clause contained information indicating which meaning of the ambiguous target word was intended in the current sentence. The design included two key manipulations. First, half of the ambiguous target words were *biased* (i.e., one of their meanings is much more frequent in the language than the other; e.g., "port" refers to a place where boats dock much more frequently than to an alcoholic beverage) or *nonbiased* (i.e., two meanings have similar frequencies in the language; e.g., "pitcher" refers to containers and baseball players with similar frequencies). Second, the disambiguating clause appeared either after the clause containing the target word (Sentences O and Q) or before the clause containing the target word (Sentences P and R). For biased words, the disambiguating clause always supported the subordinate meaning.

O. Of course the *pitcher* (*whiskey*) was often forgotten because it was kept on the back of a high shelf.
P. Because it was kept on the back of a high shelf, the *pitcher* (*whiskey*) was often forgotten.
Q. Last night the *port* (*soup*) was a great success when she finally served it to her guests.
R. When she finally served it to her guests, the *port* (*soup*) was a great success.

Because of the complexity of the design, Duffy et al.'s results are most easily understood if described in terms of the example sentences above, although of course the pattern reported was based on mean reading times across items in each condition. First, for Sentence O, reading times were longer on the word "pitcher" than on "whiskey." Given that ambiguous targets and unambiguous control words were matched for word frequency, EBRW would assume that both words have a similar number of instances stored from prior encounters. However, about half of the instances for "pitcher" include the container meaning, whereas the other half include the baseball player meaning, so each next instance retrieved has the potential to direct the random walk toward a different threshold. Thus, more retrievals would be needed to reach one of the thresholds for "pitcher" than for "whiskey," in which all instances direct the random walk toward the same response threshold. This analysis also suggests that the random walk would only reach the contextually appropriate threshold about half of the time for "pitcher"; consistent with this idea, reading times in the subsequent disambiguating region of the sentence were longer after "pitcher" versus "whiskey," presumably reflecting reanalysis.

In contrast, for Sentence P, reading times did not differ significantly on the word "pitcher" versus "whiskey." To revisit, EBRW assumes that the speed with which instances are retrieved is a function of the similarity of those instances to the current stimulus. A reasonable additional assumption is that each prior instance contains not only the interpretation of the target word but also information about the context in which it was encountered (an assumption that will be revisited in Section 4.3.2). If so, contexts in which ‘‘pitcher’’ referred to a container are likely to be more similar to one another—and importantly, to the current context preceding the ambiguous word—than contexts in which ‘‘pitcher’’ referred to a baseball player. Thus, ‘‘container’’ instances would outrun ‘‘baseball player’’ instances on average, functionally minimizing competition from the ‘‘baseball player’’ instances and expediting the walk toward the threshold for the contextually appropriate container meaning.[3]

Similar to the pattern in Sentence P, reading times in Sentence Q did not differ significantly on the word ‘‘port’’ versus ‘‘soup,’’ but presumably for a different reason. Given that ‘‘port’’ is biased, most of its instances include the boat dock meaning, whereas relatively few include the alcoholic beverage meaning. Given that the preceding context does not favor either meaning, all instances presumably have the same average retrieval speed. Thus, ‘‘boat dock’’ instances are much more likely to be retrieved based on frequency alone, directing the random walk quickly toward the dominant meaning (cf. the unambiguous control word ‘‘soup,’’ in which all instances direct the random walk toward the same response threshold). In this case, the dominant meaning turns out to be contextually incorrect, and in fact reading times in the subsequent disambiguating region are elevated relative to the control condition.

Finally, in Sentence R, reading times were longer for ‘‘port’’ than for ‘‘soup.’’ Although ‘‘alcoholic beverage’’ instances now have the advantage of faster retrieval speed due to greater similarity with the current context, it is presumably not enough to completely overcome their disadvantage with respect to frequency. Thus, ‘‘alcoholic beverage’’ and ‘‘boat dock’’ instances both remain competitive in this race, the former due to similarity and the latter due to frequency. Elevated reading times for ‘‘port’’ presumably reflect the greater number of retrievals needed to overcome competition from ‘‘boat dock’’ instances in the walk toward the ‘‘alcoholic beverage’’ threshold. Of course, the random walk process allows for the possibility that the contextually inappropriate ‘‘boat dock’’ threshold is reached on some trials, in which case elevated reading times may also partially reflect reanalysis to reconcile with the preceding context.

To explain this pattern (which subsequently has been termed the *subordinate bias effect*), Duffy et al. (1988) proposed a *reordered access model*, according to which ‘‘prior disambiguating context serves to increase the

[3] A potential problem for EBRW (and memory-based theories in general) is the finding that reading times on ‘pitcher’ and ‘whiskey’ were similar. Although the context in Sentence P would increase retrieval speed for ‘container’ instances over ‘baseball player’ instances of ‘pitcher’, there would still be about half as many ‘container’ instances for ‘pitcher’ as the total number of instances for ‘whiskey’. Thus, EBRW would expect reading times to be faster for ‘whiskey’ than for ‘pitcher’ based on frequency alone. Although resolution of this issue must await further investigation, one possible explanation is that the contexts used in Duffy et al.’s sentences are more consistently similar to contexts in which the ambiguous words appear than to contexts in which the unambiguous words appear. If so, the frequency disadvantage could be offset by a similarity-based advantage in retrieval speed for ‘container’ instances of ‘pitcher’.

availability of the appropriate meaning without inhibiting the inappropriate meaning'' (p. 437). However, they state that ''we are deliberately avoiding a specification of the mechanisms by which context affects access'' (p. 431). The theoretical account that EBRW provides is largely consistent with the reordered access model, in that it assumes that context increases the retrieval speed of instances with the appropriate meaning. However, EBRW provides a specification of the mechanism that underlies the interplay between frequency and contextual information.

4. Investigating Automaticity in Reading Comprehension: Outstanding Issues

To summarize, several recent studies have directly tested predictions of memory-based theories of automaticity in reading comprehension and have provided foundational evidence for the role of memory-based automatization in syntactic and semantic processes. Further support for the viability of memory-based automatization in reading comprehension comes from the facility with which memory-based theories—EBRW in particular—provide relatively straightforward explanations for findings reported in earlier research on syntactic and lexical processes. Taken together, the direct and indirect evidence suggests that memory-based processing may play a significant role in the automatization of reading comprehension processes. Below, I outline several key directions for future research and further theory development to address outstanding issues concerning the nature of automaticity in reading comprehension.

4.1. Generality of Memory-Based Automaticity in Reading Comprehension

On one hand, the work summarized above makes significant strides toward establishing the generality of memory-based automatization in reading comprehension. My colleagues and I have found evidence for shifts from algorithm to retrieval in two different comprehension processes, across delays, and when linguistic units are transferred to new contexts (Rawson, 2004; Rawson & Middleton, 2009; Rawson & Touron, 2009). On the other hand, the available evidence represents only the first of many steps that must be taken to establish the extent to which memory-based processing underlies automaticity in reading comprehension, when one considers the sizeable number of component processes involved in reading comprehension. Furthermore, a given component may process several different kinds of input. For example, Rawson focused on the resolution of MV/RR syntactic ambiguities, but this represents only one of many syntactic structures processed by the syntactic parsing system.

As discussed in Section 2.2, several different mechanisms are thought to contribute to practice effects on the speed and accuracy of cognitive task performance. Automaticity theorists are forthcoming in acknowledging that any given mechanism may play a prominent role in some cognitive tasks but contribute minimally in others (e.g., Blessing & Anderson, 1996; Haider & Frensch, 1996; Logan, 1988). Thus, evidence for the role of memory-based processing in interpreting one type of syntactic structure (MV/RR ambiguity) and one type of conceptual combination (noun–noun combinations) does not ensure its involvement in other components of reading comprehension. Fortunately, a strength of memory-based theories of automaticity is that they afford straightforward predictions concerning components in which memory-based automatization is more versus less likely to play a role during reading comprehension.

To illustrate, consider the factors that determine the involvement of memory-based processing according to EBRW. First, the extent to which interpretation is based on retrieval depends on the likelihood that retrieval beats the algorithmic route in the race to produce an interpretation. Thus, the role of memory-based processing will depend both on retrieval speed and on algorithm speed. As currently formulated, EBRW assumes that retrieval speed is largely determined by three factors: the number of stored instances (increasing the number of runners in the race increases the likelihood that one will finish quickly), the similarity of those instances to the current stimulus (more similar instances run more quickly), and the number of mutually exclusive interpretations stored across the various instances (in EBRW, any step toward one response threshold is a step away from others, so the number of competitors will tend to increase the time it takes for the walk to reach any one threshold).

Accordingly, EBRW first predicts that memory-based processing will play a role in a given reading component to the extent that particular tokens of the type processed by that component repeat frequently in the language. Logically, smaller units of information repeat more frequently than larger units composed of those constituents. For example, a token phoneme repeats more frequently than any of the token words that contain it. Likewise, a token word repeats more frequently than any of the token phrases that contain it. More generally, this leads to the prediction that the involvement of memory-based processing will be negatively related to the grain size of the informational unit.

However, EBRW suggests two qualifications to this basic prediction. First, the advantage of frequency may be offset to the extent that the interpretations stored in those instances are inconsistent with one another. For example, the relative clause "that he visited" is encountered much less frequently than the pronoun "he." However, retrieved instances of the syntactically unambiguous "that he visited" will consistently direct the walk toward the OR-clause threshold. In contrast, "he" has been used to refer to a functionally infinite number of different people or entities, and thus retrieval of instances containing interpretations of "he" are unlikely to reach one response threshold. As a result, memory-based processing is more likely to contribute to interpretation of the larger syntactic unit than the smaller pronoun constituent within it (more generally, EBRW would predict that memory-based processing plays a negligible role in establishing the referents of pronouns).

The second qualification to the prediction of a negative relationship between memory-based processing and information grain size concerns algorithm speed. A smaller set of stored instances may be more competitive against a slow algorithm than a larger set of stored instances would be against a fast algorithm. For example, consider conceptual combination. Prior research in which novel conceptual combinations are presented for speeded judgments of sensibility have reported response times between 1000 and 1500 ms (e.g., Gagné & Shoben, 1997; Storms & Wisniewski, 2005), suggesting that algorithmic processing of conceptual combinations is relatively slow (at least as compared to the speed of sublexical and lexical processes). It is perhaps not surprising then that the automaticity research involving conceptual combinations showed that retrieval was fast enough to reliably beat the algorithm after only 2–7 repetitions of unfamiliar conceptual combinations (Rawson & Middleton, 2009, Rawson & Touron, 2009, and the unpublished study reported in Section 3.1.2).

Thus, EBRW supports predictions regarding differences in the involvement of memory-based automatization across components of the reading comprehension system. Likewise, EBRW also predicts systematic variability in the role of memory-based automatization within a particular component, given differences between tokens in their frequency and the degree of similarity across encounters. EBRW's account of variability within a system may also potentially provide some explanation for mixed results within areas of reading comprehension research. For example, several studies have replicated the subordinate bias effect described in Section 3.2.3 (e.g., Binder & Rayner, 1998; Folk & Morris, 2003; Kambe, Rayner, & Duffy, 2001). However, other lexical ambiguity studies have failed to find subordinate bias effects, instead reporting findings that appear to suggest selective activation of subordinate meanings of ambiguous words (e.g., Martin, Vu, Kellas, & Metcalf, 1999; Vu, Kellas, Metcalf, & Herman, 2000; Vu, Kellas, & Paul, 1998). Subtle differences between studies in the absolute and relative frequencies of target words and their meanings as well as strength of contextual support have been implicated in these apparent inconsistencies, and EBRW provides a relatively straightforward account of how these factors would produce different patterns of performance.

Finally, to the extent that memory-based automatization is less likely to contribute directly to higher level comprehension components (those that process larger units of information that repeat less frequently), it may still make an indirect contribution to the operation of these processes. Previous research has shown that cognitive resource demands decrease with increasing shifts from algorithmic processing to memory-based interpretation of stimuli (Klapp et al., 1991). Given evidence that the various component processes involved in the reading comprehension system share processing resources (Rawson, 2007), the shift from algorithmic processing to retrieval in lower level components may free processing resources for faster and more accurate operation of higher level components. Additionally, the outputs of lower level components are often the input to higher level components, and thus retrieval-based processing at lower levels will benefit higher level processing by providing their input more quickly.

4.2. Individual Differences in Memory-Based Automaticity

Another issue concerns the extent to which memory-based theories (and other process-based theories of automaticity more generally) can explain individual differences in reading comprehension skill, including differences between age groups as well as proficiency differences between readers within an age group. Currently, only one study has directly examined age differences in memory-based automatization in reading comprehension (Rawson & Touron, 2009), and no study has directly examined the role of memory-based automaticity in proficiency differences between same-age readers.

Regarding age differences, Rawson and Touron (2009) found relatively minimal differences between younger and older adults in memory-based automaticity. To revisit, both age groups showed the two empirical footprints of memory-based automatization (i.e., diminishing effects of algorithm complexity and item-specific practice effects). Although older adults initially appeared to require more trials of practice to shift to memory-based processing, results from the second experiment indicated that older adults' slower shift was due to reluctance to rely on retrieval rather than to memory deficits. This pattern is perhaps surprising, given earlier research establishing age differences in simple associative learning during both encoding and retrieval (e.g., Dunlosky, Hertzog, & Moman-Powell, 2005; Old & Naveh-Benjamin, 2008). These findings support the expectation that older adults would have poorer encoding of instances during reading and/or greater difficulty retrieving those instances on subsequent encounters of repeated stimuli. However, in Rawson and Touron's experiments, all practice was contained within one practice session and no transfer task was administered. To the extent that older adults experience greater forgetting across delays (Giambra & Arenberg, 1993; Jenkins & Hoyer, 2000), the possibility remains that older adults will show reduced memory-based processing due to memory deficits after a delay. Likewise, age differences in the involvement of memory-based processing may emerge when items are reencountered in new contexts.

At the other end of the age continuum, developmental research is clearly needed to directly investigate the role of memory-based automatization in reading comprehension for younger children. An increasing amount of developmental research has documented associations between the fluency of young children's language processing and statistical regularities in the language (e.g., Bannard & Matthews, 2008; Kidd, Brandt, Lieven, & Tomasello, 2007; Saffran, 2003). Accordingly, memory-based theories show promise for providing a unified theoretical framework for understanding how beginning readers transition to skilled reading.

Regarding proficiency differences between readers within an age group, an intriguing possibility is that higher-skill and lower-skill readers differ in the involvement of memory-based processing during reading. Greater reliance on retrieval versus algorithmic processing would explain faster reading speeds for higher-skill versus lower-skill readers (e.g., Bell & Perfetti, 1994; Jackson, 2005; Jenkins, Fuchs, van den Broek, Espin, & Deno, 2003). Additionally, the idea that memory-based processing in lower level reading components indirectly benefits higher level components (see Section 4.1) would explain better performance on comprehension tests for higher-skill versus lower-skill readers. Memory-based processing may also lead to faster and more accurate processing to the extent that interpretations based on item-specific biases are more likely to be correct than interpretations based on item-general biases (e.g., for the DO/SC ambiguities described in Section 3.2.1, memory-based interpretation for verbs biased toward SC structures would avoid errors and reanalysis costs from adopting the item-general bias toward the DO structure).

Of course, this proposal begs the question of why higher-skill readers would be more likely to rely on retrieval. The most straightforward answer from EBRW would be that higher-skill readers have more stored instances, which would make retrieval more competitive against algorithmic processing. Intuitively, readers likely differ in the number of stored instances due to differences in the amount of practice (i.e., reading experience). Indeed, Stanovich and colleagues have consistently shown that measures of print exposure predict performance on various indices of reading skill, including phonological coding, orthographic knowledge, spelling, vocabulary, verbal fluency, and comprehension performance (e.g., Cunningham & Stanovich, 1991; Stanovich & Cunningham, 1992; Stanovich & West, 1989; West & Stanovich, 1991). Although suggestive, findings involving coarse-grain measures of this sort do not uniquely support memory-based theories of automaticity (e.g., higher levels of practice would presumably also yield more efficient item-general algorithms) and do not diagnose the relative contributions of the various automaticity mechanisms to these associations between experience and reading skill. Nonetheless, EBRW (and memory-based theories more generally) provides a detailed specification of how the representations and processes that underlie reading comprehension change with practice and why the observed associations would arise.

Beyond individual differences in the number of stored instances, other nonexclusive factors may also underlie individual differences in the involvement of memory-based automatization in reading comprehension. First, readers may differ in the kind or quality of stored instances, due to differences in the integrity of encoding or in the information stored in each instance. In other words, two readers exposed to the same stimuli the same number of times will not necessarily (or even likely) come away with identical sets of stored instances. Second, readers may differ in the efficiency of the item-general algorithms against which the retrieval route must compete. Given the same set of stored instances, retrieval would presumably be less likely to contribute to interpretation for a reader with a highly efficient algorithm versus a reader with an inefficient algorithm. To the extent that higher-skill readers have more efficient algorithms, it is thus possible that higher-skill readers may actually show weaker evidence for memory-based processing during reading comprehension. We are currently conducting a large individual-differences study in my lab to begin exploring these possibilities.

4.3. Further Development of Memory-Based Theories of Automaticity

In large part, memory-based theories of automaticity—particularly EBRW—were successful in explaining findings discussed throughout Section 3. However, several aspects of the results considered above also revealed limitations in the theoretical assumptions of these theories. Other findings in the extant literature on reading comprehension further suggest that the assumptions of these theories will require revision if they are to provide a complete account of the role of memory-based automatization in reading comprehension. Below, I consider two key ways in which some modification of the memory-based theories would improve their explanatory power.

4.3.1. Forgetting

Several of the experiments described in Section 3.1 found evidence for forgetting across delays. For example, as shown in Figure 3, reading times were significantly slower at the outset of the second practice session than at the end of the first practice session (see also Rawson, 2004; Rawson & Middleton, 2009). Rickard (2007) has also demonstrated slowing of response times across delays between practice sessions in other cognitive tasks. The finding of forgetting across a delay is not surprising. What is surprising is that this fundamental aspect of memory has been largely ignored by memory-based theories of automaticity. As Rickard rightly noted, "a complete theory of human skill acquisition must account for the effects of the delays between sessions on learning and performance'' (p. 297). Forgetting is likely to be a significant factor influencing the role of memory-based automaticity in reading comprehension in particular, given the typical time intervals between repetitions of linguistic units in natural language.

Given that memory-based theories assume that basic memory processes underlie speed-ups with practice, the addition of a forgetting parameter to reflect negatively accelerated loss of prior interpretations over time would seem straightforward (cf. the robust pattern found in accuracy measures of explicit memory; Rubin & Wenzel, 1996). Nevertheless, findings from skill acquisition research suggest that capturing the magnitude and rate of loss of memory-based automaticity across delays may not be so simple. For example, in recent research involving an alphabet arithmetic task (Wilkins & Rawson, 2009), we found markedly greater loss across a delay for item-specific practice effects (indicative of memory-based automaticity) versus item-general practice effects (indicative of gains in algorithm efficiency), which has implications for the competitiveness of retrieval against the algorithm after a delay.

Regarding rate of loss, Anderson, Fincham, and Douglass (1999) proposed that the overall strength of an item in memory is the sum of individual trace strengths that each decays as a function of the age of the trace. In their model, the age of a trace is defined in terms of number of blocks of practice (e.g., the trace for an item presented in Block 2 has an age of 6 blocks in Block 8). Importantly, to fit data both within and across sessions, the estimate of age contained two components, $age = x + m * H$, where x is the age of the trace in blocks at the end of a practice session, m is the number of days between the previous session and the current practice session, and H is the number of blocks equivalent to the elapse of 1 day. Across experiments, estimates of H ranged from 4.6 to 14.0, with an average of 9.8. So, the trace of an item presented in Block 1 of a 20-block practice session would be 19 blocks old at the end of the session but would only age another 19.6 blocks across the next 2 days. Based on these parameter estimates, Anderson et al. proposed that ''clock time is not the right way to think of the critical variable. It might indicate that the critical variable is the number of intervening events and that there are fewer of these after the experimental session ends'' (p. 1123). This interpretation highlights why developing more complete models of memory-based automaticity in reading comprehension may not be a simple matter. In general, more powerful memory-based theories would not only assume that loss occurs but would also include explicit assumptions concerning why loss occurs (e.g., interference from intervening events).

4.3.2. What's in an Instance?

This question represents perhaps the greatest challenge for fully understanding the role of memory-based automatization in reading comprehension. Virtually all prior research on memory-based theories has involved simple cognitive tasks (e.g., alphabet arithmetic, dot counting). In these tasks, the stimulus is discrete (e.g., A + 2), there is only one processing goal for that stimulus (find the sum), there is only one possible solution (A + 2 always equals C), and the context in which the problem is encountered does not matter. Although a small number of automaticity studies have examined other aspects of the information encoded in an instance (e.g., Logan, 1990; Logan, Taylor, & Etherton, 1996), the implicit or explicit assumption in most research on memory-based theories is that instances simply contain information about a discrete, unambiguous stimulus and a response.

In contrast, in reading comprehension, the functional stimulus is much less obvious—when reading a textbook chapter, is a ‘‘stimulus’’ the chapter, paragraph, sentence, clause, phrase, word, morpheme, phoneme, or alphanumeric character? Additionally, for a stimulus at any given grain size, there is usually more than one processing goal—for a given word, processing goals include word identification, syntactic role assignment, meaning assignment, and thematic role assignment.[4] Furthermore, as repeatedly illustrated in discussion of prior research in Section 3, many linguistic stimuli afford more than one possible interpretation. Moreover, the context in which a linguistic stimulus is encountered clearly does influence processing. Thus, the answer to ‘‘What's in an instance?’’ seems much less straightforward in reading comprehension.

A reasonable starting assumption consistent with memory-based theories is that the stimulus is defined by the grain size of the linguistic unit handled by a particular interpretive process, and what is stored in an instance is the stimulus plus the interpretation generated by that process. Consider the simple sentence, ‘‘The veterinarian found the calf.’’ For meaning assignment, syntactic role assignment, and thematic role assignment, the grain size of the stimulus is presumably the word. Assuming that these are three separate processes, applying them to the three content words in ‘‘The veterinarian found the calf’’ would yield nine instances, as illustrated in Panel A of Figure 6.

However, this simplistic account is ill-equipped to handle many findings in the literature. For example, various sources of evidence suggest that the language processing system is sensitive to probabilistic information about associations between word meanings, syntactic roles, and thematic roles (e.g., thematic agents are most commonly subjects, and thematic patients are most commonly direct objects). Similarly, syntactic category information can influence the resolution of word meaning (e.g., the noun ‘‘duck’’ refers to a waterfowl, whereas the verb ‘‘duck’’ refers to a crouching motion; Folk & Morris, 2003). Furthermore, not all reading comprehension theories assume

[4] In lay terms, thematic roles concern who did what to whom, when, where, and with what.

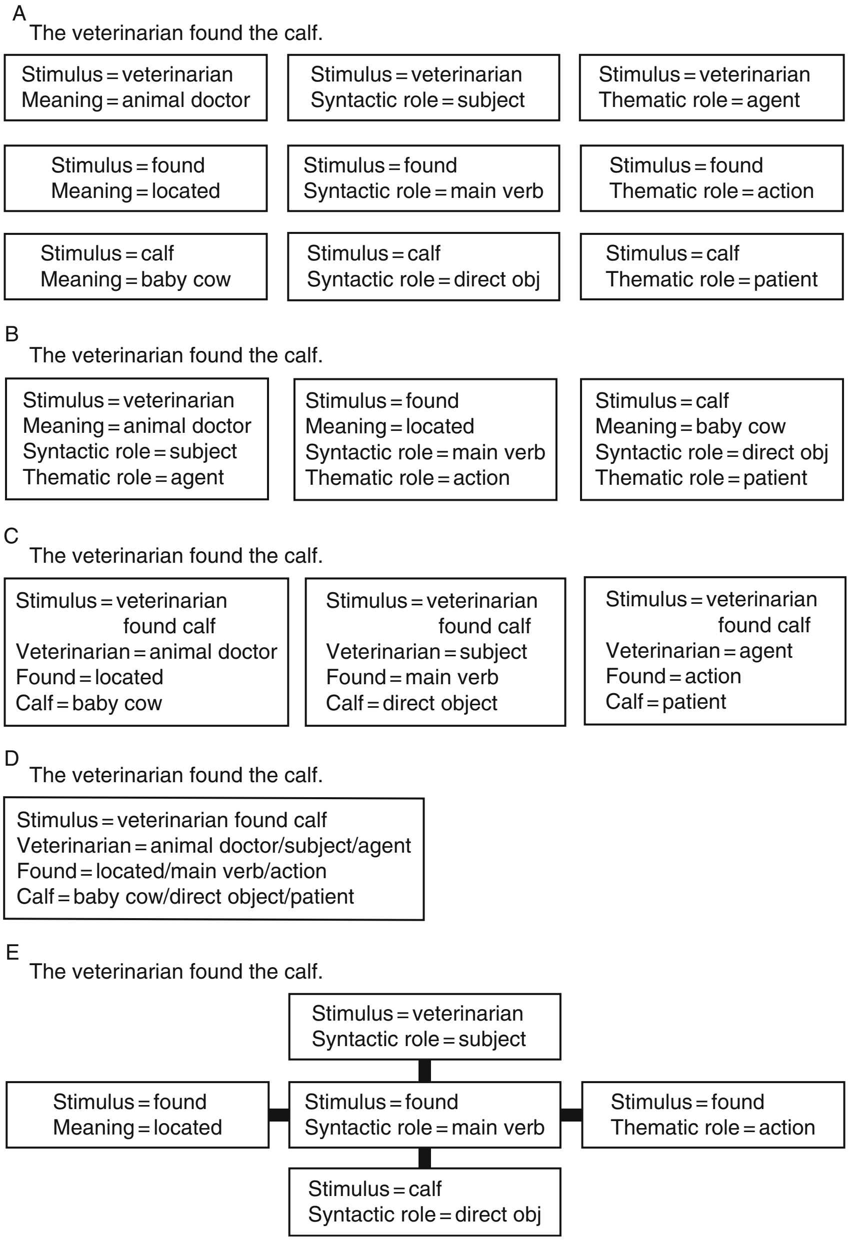

Figure 6 Panels A–E each represent the number and content of instances stored from processing the example sentence based on different theoretical assumptions about what information is stored in an instance (see Section 4.3.2 for further explanation).

that meaning assignment, syntactic role assignment, and thematic role assignment are separate processes (MacDonald, Pearlmutter, & Seidenberg, 1994). If so, another possibility is that instances for a given word contain multiple kinds of interpretive information (see Panel B in Figure 6).

However, even these more information-rich instances are insufficient to account for some of the findings discussed in Section 3. For EBRW to explain the verb bias effects described in Section 3.2.1, I added the assumption that instances stored from prior encounters include not only information about the syntactic role of the verb itself (e.g., ‘‘found’’ = main verb) but also about the larger syntactic structure in which it participated. Of course, syntactic role assignment is just one aspect of syntactic processing, which also involves representing the grammatical relationships between words in a sentence. Given that the functional stimuli for syntactic parsing processes include multiword phrases, the instances generated would thus include the syntactic structure information assumed to underlie verb bias effects (as in Panel C of Figure 6, either in addition to or instead of the more atomic instances depicted in Panels A and B). Supralexical instances of this sort would also support EBRW's account of the OR/SR clause research described in Section 3.2.2.

Hare et al.'s (2003) demonstration of sense-specific verb biases (e.g., ‘‘found’’ is more likely to take a direct object when it means ‘‘locate’’ vs. ‘‘realize’’) further suggests that verbs participate in instances containing both meaning and syntactic structure information (as in Panel D of Figure 6). Superordinate instances of this sort may also support EBRW's interpretation of the subordinate bias effect described in Section 3.2.3, which required the assumption that prior instances of ambiguous words contain information about the context in which the word was encountered along with the word's meaning in that context. However, increasingly hefty instances begins to strain the starting assumption that what is stored in an instance is the stimulus plus the interpretation generated by a particular process—what process would generate instances of this sort? An alternative to assuming superordinate instances would involve revising the assumption currently held by memory-based theories that instances are independent of one another, to permit associations between atomic instances that are generated concurrently by different processes (Panel E of Figure 6).

More generally, the preceding discussion suggests that theoretical assumptions about what information is represented in an instance should be constrained by theories of reading comprehension. Further interplay between automaticity theories and reading comprehension theories will likely benefit both domains, to the extent that it leads to further specification of what information is ultimately represented in memory as a consequence of language processing.

5. Redefining Automaticity in Reading Comprehension

Although much of the discussion above was focused on evaluating the viability of one class of process-based account (memory-based theories, with particular emphasis on EBRW) for explaining automaticity in reading comprehension, the intent was also to illustrate the promise of process-based theories of automaticity for advancing our understanding of reading comprehension more generally. First, given that process-based theories are concerned with explaining how the representations and processes that underlie task performance change with practice, they promote research questions that treat reading comprehension as a dynamic and probabilistic system rather than questions about static, dichotomous end states. For example, an issue of heated debate for several years within the reading comprehension literature concerned which kinds of inference were made automatically and which were not (McKoon & Ratcliff, 1992; Singer, Graesser, & Trabasso, 1994), with particular focus on which inferences were fast and obligatory. In contrast to the dichotomous questions that often arise from property-based debates (e.g., Are causal inferences fast? Are causal inferences obligatory?), process-based theories of automaticity motivate more dynamic, probabilistic questions (e.g., How does the speed and/or likelihood of causal inferences change with experience, and why?).

Second, process-based theories of automaticity may provide unified accounts of many different language processing phenomena both within and across research areas. Within an area of research on a particular reading comprehension process (e.g., conceptual combination), some theories may focus on the processing of novel stimuli (e.g., Estes, 2003; Wisniewski & Middleton, 2002), whereas other theories focus on the processing of familiar stimuli (e.g., Andrews, Miller, & Rayner, 2004; Juhasz, Inhoff, & Rayner, 2005). Process-based theories of automaticity can provide the missing link by describing how stimuli transition from novel to familiar. Process-based theories of automaticity also provide theoretical architectures that can unify accounts of language processing across areas of research on different component processes. For example, as illustrated here, EBRW provides a unitary theoretical account of item-specific practice effects in lexical ambiguity resolution, syntactic parsing, and conceptual combination.

Third, process-based theories change the grain size at which automaticity is conceptualized. For example, although one or more component processes within the reading comprehension system may increasingly rely on memory-based processing with practice, at least some of the component processes in the system are unlikely to do so. Thus, according to memory-based theories, it is a misnomer to describe reading comprehension as automatic. Indeed, it is likely a misnomer to describe a particular component process as automatic, except as a matter of degree. According to memory-based theories, performance is automatic when based on retrieval of prior interpretations for particular stimuli. If so, then automaticity is most precisely defined at the level of a processing episode for a particular item, and a component can only be described as automatic in relative terms (the proportion of processing episodes for which interpretation was based on retrieval of prior interpretations).

This chapter began with two key questions: What does it mean to say that reading comprehension is automatic? And how does reading comprehension become automatic? In the literature on reading comprehension, automaticity has traditionally been defined in terms of properties of performance. In contrast, I have advocated for conceptualizing automaticity in terms of underlying cognitive mechanisms that give rise to properties of interest rather than in terms of the properties themselves. Concerning what it means to say that reading comprehension is automatic, process-based theories of automaticity arguably provide more powerful and precise answers than property-list accounts. For example, according to a memory-based account, ''Automaticity is memory retrieval: Performance is automatic when it is based on single-step direct-access retrieval of past solutions from memory'' (Logan, 1988, p. 493). According to the algorithm efficiency account provided by ACT-R, ''To an approximation, we may say that a production is automatic to the degree that it is strong'' (Anderson, 1992, p. 170). Of course, a more radical answer may involve doing away with the ''A'' word altogether. To revisit, one perennial problem with property-list accounts has been ambiguity in the necessary and sufficient properties of automaticity. Whereas one solution involves explicit declaration of definitional properties (e.g., ''Is syntactic parsing automatic, where automatic refers to fast and obligatory?''), another solution is to skip the middleman altogether (''Is syntactic parsing fast and obligatory?''). The same logic applies to process-based theories of automaticity (e.g., ''Is syntactic parsing automatic, where automatic refers to processing based on the retrieval of past interpretations of specific stimuli'' vs. ''To what extent does syntactic parsing involve retrieval of past interpretations of specific stimuli?'').

In closing, although process-based theories of automaticity will require further specification to realize their potential for more completely explaining the dynamic and complex comprehension system, these theories will promote systematic exploration of how reading comprehension processes and representations change with experience.

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