Memory & Cognition
2007, 35 (7), 1675-1684

The effects of processing time and processing rate on forgetting in working memory: Testing four models of the complex span paradigm

Annekatrin Hudjetz and Klaus Oberauer
University of Potsdam, Potsdam, Germany

Four models of working memory processes in the complex span paradigm were tested: The task-switching model of Towse, Hitch, and Hutton (1998), the interference account of Saito and Miyake (2004), and two versions of the time-based resource-sharing model of Barrouillet, Bernardin, and Camos (2004). On the basis of a reading span paradigm that used segmented sentences, the effect of processing time on the recall of words was investigated while the amount of processing was held constant. Two conditions of reading (continuous vs. normal) were compared in order to study the influence of brief pauses during reading that could be used for articulatory rehearsal. The results favor a version of the time-based resource-sharing model: A faster reading rate had a negative effect on recall. The effect of reading rate was obtained with continuous as well as normal reading, revealing that even continuous articulation does not prevent simultaneous refreshing of memory traces. A second experiment showed that continuous reading made concurrent articulatory rehearsal virtually impossible. These findings imply that a second rehearsal mechanism for verbal working memory, other than articulatory rehearsal, exists.

Working memory can be described as a system that holds a small amount of information ready for processing (Baddeley & Hitch, 1974; Cowan, 1995; Oberauer, 2002). Its capacity for maintaining information is severely constrained, and this capacity limit is an important determinant of our ability to reason (Kyllonen & Christal, 1990; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002). The nature of the capacity limit of working memory is still unclear. One important step toward understanding it would be to reveal the cognitive processes involved in tasks that have been shown to measure working memory capacity.

The most frequently used task paradigm for measuring working memory capacity is the complex span paradigm (for a review, see Conway et al., 2005). The first version of this paradigm was the reading span task introduced by Daneman and Carpenter (1980), and a variant of this task was used in the present research. In the reading span task, participants read a set of sentences, sometimes in combination with the generation of words or a judgment based on the sentences' content. Target words, usually placed at the end of a sentence, have to be remembered and recalled together at the end of a sentence set. The number of sentences in a set can be varied. Sometimes an adaptive testing procedure is used to assess a participant's span, in which set size is increased until the participant fails a recall criterion.

The purpose of this article is to distinguish among four processing models of the complex span paradigm that have received considerable attention and empirical support: The task-switching model of Towse, Hitch, and Hutton (1998, 2000), the interference hypothesis advanced by Saito and Miyake (2004), and two versions of the time-based resource-sharing model of Barrouillet, Bernardin, and Camos (2004).

The task-switching model (Towse et al., 1998, 2000; Hitch, Towse, & Hutton, 2001) emphasizes the role of time-based decay. The more time goes by, the more information decays and cannot be recalled anymore. Trace decay takes place as soon as attention is drawn away from the memory traces. Towse et al. (1998, 2000) assumed that the two requirements of the reading span paradigm (and related paradigms)—remembering some information and processing other information— are accomplished serially: People first dedicate themselves to the processing task (i.e., reading a sentence) and then switch to the encoding of the new, to-be-remembered word and rehearsal of previously encoded words, if any. As soon as the next sentence appears, attention is switched back to the process of reading, and so on. Therefore, in the complex span paradigm, forgetting occurs because the processing task draws attention away from the memory traces already encoded, leaving them to decay until the processing task is finished.

Support for the task-switching model comes from variants of reading span tasks, in which the time intervals between successive memory items (i.e., words to be re-

A. Hudjetz, annekatrin.hudjetz@uni-potsdam.de

membered) were varied. Towse et al. (1998, 2000) varied the sentence length and created two conditions: The *short-final* lists started with a long sentence and ended with a short sentence; the *long-final* lists started with a short sentence and ended with a long one. Although the overall amount of processing was the same in both conditions, the short-final lists were associated with shorter average intervals between encoding of successive memory items. This is because the memory items were the last words of each sentence, and the length of the first sentence was therefore irrelevant with regard to the intervals between memory items. In the short-final lists, participants spent less time reading from the second through to the last sentence. This implies that the time during which items already encoded into memory could have been forgotten was shorter in the short-final condition. In several experiments, Towse and colleagues found that spans were higher in the short-final than in the long-final condition.

The paradigm developed by Towse and colleagues (1998, 2000), however, confounds processing time with the amount of processing: Longer sentences not only took longer to read, they also consisted of more words to be read. The advantage of short-final lists could, therefore, also be explained by retroactive interference. Assuming that to-be-processed material finds its way into working memory, one could conclude that the processing task impairs recall by interfering with the memory traces held concurrently in working memory. In the long-final condition, more to-be-read words follow encoding of the memory items than in the short-final condition, and this could explain the lower spans found with long-final sentence sets than with short-final ones.

Saito and Miyake (2004) removed the confound of processing time and processing amount, and their findings support the interference hypothesis. They used a design similar to that used by Towse et al. (1998, 2000) but divided the sentences into segments and presented the segments one by one at a computer-paced rate. In their Experiment 3, all sentences were broken down into three segments. Longer sentences yielded segments containing more words, but they were presented for the same amount of time as the segments of short sentences. Short and long sentences therefore differed in the *amount* of processing they required, but the amount of processing *time* was held constant. To prevent rehearsal, participants were instructed to read the sentences at a continuous pace. Longer sentences, of course, required a faster reading pace than did shorter sentences. If the difference between short-final and long-final lists was due to time-based decay, that difference should have disappeared in this experiment. The interference hypothesis, however, predicted that short-final lists would still lead to better recall. Span was still higher in the short-final condition, in line with the interference hypothesis but contrary to the decay hypothesis.

In two further experiments, Saito and Miyake (2004) used equally long sentences divided into different numbers of segments. All segments were presented for the same amount of time. Different conditions were created by varying the type of sentence placed at the end of the set—a sentence with a smaller number of segments or one with a larger number of segments. The short-duration-final condition started with a six-segment sentence and ended with a three-segment one, and the long-duration-final condition presented the sentences in the reverse order. Thus, Saito and Miyake (2004) could evaluate different sentence-processing times while holding the amount of processing constant. In both of their experiments (4A and 4B), there was no difference in span between the two conditions. This goes contrary to the decay hypothesis, which predicts that longer processing times following the encoding of memory items would lead to worse recall. Saito and Miyake's result is consistent with the interference hypothesis, since the amount of material processed was held constant within each sentence across conditions.

A third account of forgetting is the time-based resource-sharing (TBRS) model of Barrouillet and Camos (2001) and Barrouillet et al. (2004). The basic idea of this model is similar to that of the task-switching account: Working memory is assumed to have a bottleneck (cf. Pashler, Johnston, & Ruthruff, 2000) that can be devoted to only one task at a time, either processing or refreshing the memory traces through retrieval. The bottleneck therefore has to switch between these two tasks when both are intertwined, as they are in the reading span paradigm. In contrast to the task-switching assumption of Towse et al. (1998, 2000), however, the TBRS model postulates that the switching does not take place at the end of one task but rather between small task steps, making use of pauses during the processing task to refresh the memory items. Recall performance is assumed to depend on the number of memory retrievals required during the processing task (i.e., the number of times a word meaning must be retrieved from semantic memory during the reading of a sentence). The ratio of retrievals to time is called *cognitive load*. Higher cognitive load results in poorer recall of list items. Despite its similarity to the task-switching account, this model makes a prediction that goes in the opposite direction: When the amount of processing, defined as the number of retrievals required by the processing task, is held constant, then increasing processing time reduces the cognitive load and therefore should lead to better recall and higher span. The logic behind this prediction is that the bottleneck can use brief pauses between two processing steps to refresh the memory traces, and with more time for the same amount of processing, there are more and longer pauses that can be used to squeeze in memory-refreshing episodes. In addition, the TBRS model predicts that when processing time is held constant, a higher amount of processing increases cognitive load and therefore leads to poorer recall and lower span, in line with the interference hypothesis.

Barrouillet and Camos (2001) and Barrouillet et al. (2004) conducted several experiments to evaluate the TBRS model and found support for both its predictions. They used variants of reading span and its close relative, operation span (Turner & Engle, 1989). The processing tasks that separated the memory items during encoding were broken down into small segments (e.g., solving a simple equation, reading a syllable aloud). These segments were presented one by one at a computer-controlled pace.

Each trial consisted of several short sequences of processing steps, each followed by a memory item (usually a letter). At the end of several such sequences, participants had to recall all of the memory items. When the number of individual processing segments between two memory items was increased while the total time between memory items was held constant (thus forcing participants into a higher processing rate), memory became worse. When the total processing time between two memory items was increased while the number of processing segments was held constant (thereby allowing a slower pace), memory performance improved.

The latter finding is at odds with the results of Saito and Miyake's (2004) Experiments 4A and 4B, which showed no effect of varying the processing time while holding the amount of processing constant. The results of Barrouillet et al. (2004) pose a problem for the interference hypothesis, which predicts that spans should not differ when the amount of processing is held constant and only processing time is varied. On the other hand, the results of Saito and Miyake are difficult to explain in terms of the TBRS model, which predicts better performance when more time is allowed for the same amount of processing. Therefore, it is important to resolve the discrepancy between the findings of these two groups of researchers. This is the goal of the present study.

We hypothesized that the different results obtained in the previous studies were a consequence of the instruction used by Saito and Miyake (2004), who instructed participants to read continuously and without pauses. By requiring continuous reading, Saito and Miyake wanted to block rehearsal interspersed between reading of the sentence segments. Rapid switching between processing and rehearsal, however, is an essential component of the TBRS model. If refreshing of memory traces is prevented by continuous reading, the differences in cognitive load in the two processing time conditions should disappear or even reverse. In our experiments, we therefore directly compared normal, unconstrained reading with continuous reading.

At this point it is important to distinguish between two forms of rehearsal of verbal material. One form, which has figured prominently in many accounts of verbal serial recall, is *articulatory* rehearsal. Barrouillet et al. (2004), however, assumed that memory traces were rehearsed or refreshed by *retrieval*, a more general mechanism that can also be applied to nonverbal material and that does not necessarily involve silent articulation. For instance, retrieval of a word could involve just its semantic representation without reactivating its phonological representation at all. Continuous as opposed to unconstrained reading can be assumed to block articulatory rehearsal, but there is no reason to assume that it blocks retrieval through a central bottleneck as envisaged by Barrouillet et al.: The central bottleneck can operate concurrently with unrelated motor processes (Pashler et al., 2000) and hence could engage in rehearsal during continuous overt articulation. Therefore, we need to distinguish two versions of the TBRS model—one in which rehearsal is based on silent articulation, which we will call TBRS–a, and one in which rehearsal is based on a retrieval mechanism that does not involve articulation, which we will call TBRS–r. Barrouillet et al. lean toward TBRS–r, but there is nothing in their data to rule out the alternative, TBRS–a. In fact, TBRS–a would help to reconcile the results of Barrouillet et al. with those of Saito and Miyake (2004) because it predicts that continuous reading will reduce or prevent rehearsal and thereby eliminate the advantageous effect of a slower processing rate. For this reason, and because articulatory rehearsal plays such a prominent role in many theories of verbal working memory, we believe that TBRS–a deserves serious consideration. As we demonstrate, the two versions of TBRS make different predictions for our experiment and therefore can be teased apart.

EXPERIMENT 1

We varied the paradigm used by Saito and Miyake (2004): Instead of manipulating duration of processing by using different numbers of segments per sentence, we divided each sentence of the same length into four segments with three words each and varied presentation duration of the segments. The presentation duration of segments was held constant within a list of sentences, so participants did not have to adjust their reading speed within one trial. We could now test different processing times while holding constant the amount of processing, without making use of short- and long-duration-final conditions. In this regard, our paradigm was similar to that of Barrouillet and colleagues (2004), who also varied processing time or processing amount throughout the whole list.

To test the hypothesis that the continuous reading instruction given by Saito and Miyake (2004) suppressed rehearsal during reading pauses and thereby eliminated the advantage of slower over faster processing in their Experiments 4A and 4B, we varied reading conditions as a between-subjects factor. We instructed one group to read aloud the presented sentences continuously, following a computer-paced tone, and instructed the other group to simply read the sentence segments aloud at their own pace within the allotted presentation time.

The four models discussed above make the following predictions for our design: The task-switching account together with the time-based decay assumption predicts a main effect of presentation duration (short vs. long) in the direction of better recall with short durations. Both versions of the TBRS model predict the contrary effect: an advantage for the condition of long presentation duration due to a smaller cognitive load. Interference models predict no effect of presentation duration in this experiment because processing amount is held constant.

A main effect of reading instruction (normal vs. continuous) is not predicted by any of the models but could be explained by each of them, since continuous reading makes an additional demand that could impair memory performance through any hypothetical mechanism of dual-task interference. The two versions of the TBRS model differ in their predictions for the interaction of reading instruction with presentation duration. TBRS–a predicts that under normal reading conditions, people can use articulatory rehearsal during reading pauses to reactivate memory traces and that this strategy benefits from longer presentation durations. With continuous reading, articulatory rehearsal would be much more difficult, and therefore the beneficial effect of longer presentation durations would disappear or even reverse. TBRS–r, in contrast, predicts that people switch a central bottleneck between the central processes of reading (i.e., word identification, speech planning) and refreshing memory items through retrieval. Longer presentation duration allows for longer pauses in between the central processes of reading, allowing more time for rehearsal; this would be the case for normal as well as continuous reading instructions. Continuous reading reduces or eliminates pauses in overt speech, but it does not reduce the cognitive pauses between central processes of reading. Retrieval-based rehearsal competes for time with central reading processes but not with articulation, so TBRS–r assumes that rehearsal can occur concurrently with overt speech. Therefore, the advantage of long- over short-presentation duration should prevail even under continuous reading instructions. Longer presentation times leave longer intervals between moments in which central reading processes are required, and even when these intervals are filled with continuous articulation, that would not prevent the central bottleneck from switching to its rehearsal duties. TBRS–r, therefore, predicts a main effect of presentation duration, with better recall for longer durations and no interaction with reading instruction.

Method

Participants

Sixty-seven students from the University of Potsdam participated in this experiment. Most of the participants were paid €6; the others received course credit. We had to exclude data from 19 participants because they either failed to comply with the continuous reading instruction ($n = 18$) or filled out the answer sheets insufficiently ($n = 1$). The age of the 48 remaining participants ranged from 18–44 years (mean = 23.48).

Materials

The experiment was based on the reading span design used by Saito and Miyake (2004). There was one between-subjects factor (reading condition: normal vs. continuous, with 24 participants assigned to each condition) and one within-subjects factor (presentation duration: short vs. long). The set size varied, with three, four, or five sentences per trial. We developed a pool of 168 German sentences, built according to a uniform schema. Each sentence consisted of 12 one- or two-syllable words and was divided into four segments of three successive words, which in most cases formed a syntactic unit (i.e., a phrase). The last word of each sentence was a noun, which participants were asked to recall at the end of each trial.

The segments were presented at a computer-controlled pace according to a moving window technique, which means that the first segment appeared left aligned on the screen, the second segment started where the first segment had ended, and so on. The missing characters were replaced by dashes. Presentation duration for each segment was 1,890 msec in the slow condition and 1,323 msec in the fast condition. These durations were determined by adjusting the slower duration in informal pilot trials to what seemed to be a comfortable, normal reading speed and then setting the speed of the faster duration to 0.7 of the speed of the slower one to reproduce the ratio of durations that Saito and Miyake (2004) used in their Experiments 4A and 4B. Segments followed each other immediately, and with the presentation of each new segment, the previous segment disappeared from the screen.

Twenty-four sentences were selected to form the practice trials, which were presented in the same order for all participants. The 144 remaining sentences were randomly ordered and divided into 36 sentence sets, one set for each trial. There were six trials at each set size of three, four, or five sentences each for both the short- and the long-presentation durations. The two conditions of presentation duration were varied between two blocks of trials, the order of which was counterbalanced across the participants within each condition of reading.

Procedure

All stimuli were presented in black, 8-point Courier font on a white background on a computer screen. First, the participants read the instructions, which appeared on the screen and explained the task and the reading demands. The participants had the opportunity to ask questions, since the experimenter stayed in the room until the practice trials had been completed. We recorded the practice trials to insure that the participants adhered to the reading instructions.

Normal reading condition. The presentation of the instructions was followed by an announcement of what the presentation duration (slow or fast) of the next block of trials would be; then the words "practice trials" were displayed, and three practice trials were presented for the announced presentation duration in ascending order of set size (three, four, or five sentences). At the beginning of each sentence set, the participants were informed what the next set size would be; they started the trial by pressing the space bar. Following each trial, a question mark and the number of words to be recalled appeared, and the participants attempted to write the target words on an answer sheet in correct serial order. The participants pressed the space bar to move on to the next trial. Following the practice trials, a screen displaying "test trials" appeared, and 18 sentence sets in the first presentation duration were presented. Before continuing with the 18 trials of the second presentation duration, participants again worked through three practice trials in ascending order of set size demonstrating the new presentation duration. The end of the experiment was indicated when "Thank you for participating. Please contact the experimenter" appeared on the screen.

Continuous reading condition. This condition differed from the normal reading condition only by the addition of a regular sequence of tones synchronized with the appearance of the sentence segments. The participants were instructed to read the sentences aloud at a constant pace according to the rhythm of the tones. Each word had to be synchronized with one tone, so two-syllable words had to be read as fast as one-syllable words. Participants were also told that the reading had to be continuous, with no pauses at the end of the sentences. The tones lasted 20 msec and were played at a steady rhythm, every 610 msec in the slow condition and every 421 msec in the fast condition. Three tones were presented in advance of the first segment of each sentence set. Thus, participants were able to get used to the speed and could start reading aloud in time with the rhythm of the tones as soon as the first words appeared. If the participants did not succeed at the reading as instructed, the experimenter demonstrated the continuous reading in the course of the first practice trials and corrected the participants' reading in the last practice set if still necessary. Since reading was recorded, continuity could be controlled afterward. Data from participants who made more than three pauses during the whole experiment (a pause being defined as a period of silence lasting for a whole interval between two successive tones) were excluded from analysis. Figure 1 presents a schematic illustration of the experiment contrasting slow and fast presentation durations, using a set size of three sentences as an example.

Data Scoring and Analysis

For our statistical analyses, we used an alpha level of .05. For dependent variables, we computed two scores: a reading span score following Daneman and Carpenter (1980) and a total span score.

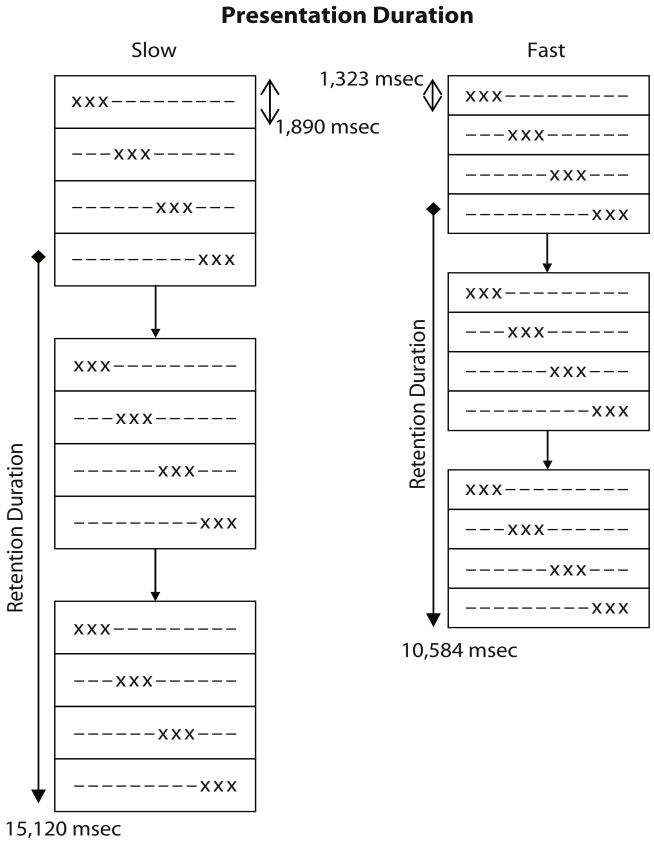

Figure 1. Schematic illustration of the experiment contrasting longer and shorter presentation durations for a three-sentence set. Each "x" represents a word.

Reading span was defined for each participant as the value of the largest set size that the participant was able to recall correctly in at least two thirds of the trials. If the participant was able to solve one third of the next largest set size, 0.5 points were added to the score. For example, if a participant solved five out of six trials of the three-sentence sets, three out of six trials of the four-sentence sets, and none of the five-sentence set trials, the calculated reading span would be 3.5. Since we did not use adaptive testing, the maximum reading span one could receive in our experiment was 5.0 (i.e., equivalent to the largest set size used).

The total number of correctly recalled target items across all sentence sets defined the total span. We counted as correct only items written on the correct line of the answer sheet. The maximum total span was 72, since a total of 72 sentences were presented in the 18 trials of one condition of presentation duration.

Results

We used a mixed-factors ANOVA to evaluate the effects of presentation duration (slow vs. fast) as the within-subjects factor and reading type (normal vs. continuous) as the between-subjects factor.

With reading span as the dependent variable, there was a significant main effect of presentation duration [$F(1,46) = 12.89$, $p < .001$, $\eta_p^2 = .219$] and a main effect of reading [$F(1,46) = 4.51$, $p = .039$, $\eta_p^2 = .089$]. Reading span was higher in the condition of slow presentation duration, confirming the prediction of Barrouillet et al.'s (2004) TBRS model. Also, performance was better in the normal reading group than in the continuous reading group. The interaction between presentation duration and reading condition was not significant [$F(1,46) = 0.13$, $p = .716$, $\eta_p^2 = .003$]. Means and standard deviations can be found in Table 1.

The results of the total span analysis were equivalent to the reading span results, yielding even stronger effects. Again, a significant main effect of presentation duration was obtained [$F(1,46) = 34.41$, $p < .001$, $\eta_p^2 = .428$] as well as a main effect of reading condition [$F(1,46) = 10.06$, $p = .003$, $\eta_p^2 = .179$]. The interaction was not significant [$F(1,46) = 1.44$, $p = .237$, $\eta_p^2 = .030$]. Table 2 presents the means and standard deviations.

Discussion

This experiment tested predictions from four models of performance in the complex span task. The results matched the predictions of TBRS–r, the version of the TBRS model of Barrouillet et al. (2004) in which rehearsal is assumed to be based on a central bottleneck and not on subvocal articulation. The results contradict the task-switching model: With longer presentation duration, performance did not decline but rather improved. The results are also difficult to explain with an interference account alone. The amount of material processed was the same with both long and short presentation durations, and therefore an interference account has no mechanism to explain why performance was better with longer presentation durations. This improvement can be explained by the assumption of Barrouillet et al. (2004) that longer presentation durations permit rehearsal in between individual processing steps of reading.

The lack of an interaction between presentation duration and reading instruction goes against the prediction of TBRS–a, in which rehearsal is assumed to be articulatory in nature. Articulatory rehearsal should be much impaired under continuous reading, which leaves very little, if any, time for squeezing in the articulation of one or more memory items. TBRS–a therefore predicts that longer presentation durations should not be beneficial when reading is continuous. If rehearsal is completely eliminated by continuous reading, the effect of presentation duration should actually reverse, since in the absence of rehearsal, longer presentation durations imply more decay. We found that the advantage of long presentation durations was as strong with continuous as with normal reading, which calls into question the rehearsal assumption of the TBRS–a variant.

The logic of our argument above hinges on the assumption that normal reading allows participants to squeeze in

Table 1
Mean Reading Spans and Standard Deviations by Presentation Duration and Reading Condition in Experiment 1

	Longer Duration		Shorter Duration	
Reading Condition	Mean	*SD*	Mean	*SD*
Normal	4.10	0.86	3.65	0.83
Continuous	3.71	1.02	3.15	0.80

Table 2
Mean Total Spans and Standard Deviations by Presentation Duration and Reading Condition in Experiment 1

	Longer Duration		Shorter Duration	
Reading Condition	Mean	*SD*	Mean	*SD*
Normal	63.17	6.00	58.54	7.54
Continuous	56.92	10.13	49.92	10.75

short phases of articulatory rehearsal to compensate for decay, whereas continuous reading prevents or strongly reduces articulatory rehearsal. We attempted to test this assumption in Experiment 2.

EXPERIMENT 2

This experiment served to measure how well people could articulate additional words while reading sentences under the conditions of Experiment 1. We asked two new groups of participants from the same population to read aloud the sets of sentences used in Experiment 1 under the same conditions (each group was assigned to one of the two reading conditions) and, concurrently, to say aloud a single one-syllable word as often as possible. The number of times participants could say the given word in addition to reading aloud five sentences provides an estimate of how many words could have been rehearsed by subvocal articulation in one trial of a five-sentence set in Experiment 1. We expected that in the normal reading condition, participants would be able to utter the additional word much more often than they would in the continuous reading condition, in which the number of utterances of the additional word should be close to zero. Moreover, we expected an interaction between reading condition and reading rate: In the normal reading condition, a slow reading rate (i.e., a longer presentation duration) should allow more frequent articulation of the additional word than a fast rate (i.e., shorter presentation duration) would; in the continuous reading condition, reading rate should make little difference.

Method

Participants. Participants comprised 20 students from the University of Potsdam who took part in a single session of less than 1 h for course credit. Their mean age was 24.6 years ($SD = 5.4$), and all but one were female. Half of them were allocated at random to the normal reading group and the other half to the continuous reading group.

Materials and Procedure. The materials consisted of the same sentences used in Experiment 1. They were arranged into 32 sets of five sentences each. The sentences were presented in segments as in Experiment 1, using the same timing parameters. The five sentences of each set were presented in a continuous sequence without breaks between sentences. The participants were instructed to read the sentences aloud as they appeared on the screen. Before each set of five sentences, they were shown a new one-syllable word on the screen, which they were instructed to say aloud as often as possible as they read the five sentences. The experiment started with 2 practice trials and 14 test trials with long-presentation duration, followed by 2 practice trials and 14 test trials with short-presentation duration. The first practice trial for each presentation duration involved only reading the sentences; in the second practice trial, the dual-task assignment of reading and saying the additional word aloud was introduced. In the continuous reading group, the participants were instructed to read in synchrony with the tones, as the participants in Experiment 1 did.

Results and Discussion

Only sentences read correctly, according to the instructions, were included in the analysis. This filter served mainly to eliminate sentences not spoken in synchrony with the tones in the continuous reading condition; as in Experiment 1, we eliminated sentences read with pauses longer than the interval between two tones. In addition, a few sentences in both reading conditions were eliminated because of reading errors. From the normal reading group, we included data from an average of 69.4 and 67.6 sentences per participant (out of 70 test sentences read) of long- and short-presentation duration, respectively. In the continuous reading group, an average of 47.7 (long) and 46.6 (short) sentences per participant remained to be analyzed.

Table 3 presents the mean number of additional words spoken in a set of five sentences, broken down by group and presentation duration. In the normal reading group, the word spoken was always the word given, but in the continuous reading group, the participants sometimes forgot the additional word or uttered a different word, and therefore we tabulated the frequency of their repeating the correct word separately.

The data show that normal reading left substantial room for articulating single words in between reading the sentence segments. The number of utterances declined with shorter presentation duration but remained high enough to permit several repetitions of a whole list of five words. In the continuous reading condition, in contrast, repetition of the additional word was close to floor level, with only a small difference in the results from long- and short-presentation durations.

This impression was confirmed by an ANOVA with reading condition as the between-subjects factor and presentation duration as the within-subjects factor conducted on the mean frequencies of repetitions of the correct word (i.e., the results found in the bottom half of Table 3; the results were the same for repetitions of all words, represented in the top half of the table). There was a main effect of reading condition [$F(1,18) = 17.76, p < .001, \eta_p^2 = .50$] and of presentation duration [$F(1,18) = 11.17, p = .004, \eta_p^2 = .28$] and an interaction [$F(1,18) = 7.55, p = .013, \eta_p^2 = .30$]. Separate tests in each group showed that the effect of presentation

Table 3
Mean Frequencies and Standard Deviations of Additional Words Spoken During a Set of Five Sentences in Experiment 2

	Normal Reading		Continuous Reading	
Presentation Duration	Mean	*SD*	Mean	*SD*
Slow (all words)	36.9	25.9	4.0	4.6
Fast (all words)	28.1	17.2	3.3	4.7
Slow (correct word)	36.9	25.9	3.6	4.7
Fast (correct word)	28.0	17.2	2.7	4.5

duration was significant in both groups: [$t(9) = 3.06$, $p = .014$] in the normal reading group and [$t(9) = 2.82$, $p = .02$] in the continuous reading group.

Continuous reading reduced the opportunity to articulate additional verbal material by a factor of 10 relative to normal reading. In the normal reading condition, slow reading allowed for substantially more additional articulation than did fast reading. The difference between slow and fast reading was also reduced by a factor of 10 in the continuous reading condition. The number of times the additional word could be articulated in the present experiment gives an estimate of how often participants could rehearse the memory material in Experiment 1 by silent articulation. In the context of the TBRS–a model, this finding implies that with continuous reading, the cognitive system can do very little to counteract decay. The occasional articulation of two or three memory items cannot be assumed to fully compensate for the loss from decay. The prediction of TBRS–a for the continuous reading condition therefore must be the following: With long presentation duration, there is more opportunity for decay, and there is little rehearsal to counteract this effect. Even though with a slow reading rate, participants could articulate, on average, one more word per trial than they could with fast reading, this was hardly sufficient to neutralize the larger amount of decay suffered in the slow reading condition. The data of Experiment 1, however, show better performance with longer presentation duration (i.e., slow reading). Given the results of Experiment 2, we see no way a purely articulatory rehearsal mechanism can generate this benefit of long presentation duration under conditions of continuous reading. Therefore, Experiments 1 and 2 together rule out TBRS–a.

GENERAL DISCUSSION

In the present study, we tested four hypotheses about the nature of forgetting and the processes of maintenance in working memory: the task-switching model (Towse et al., 1998, 2000), the interference hypothesis (Saito & Miyake, 2004), and two versions of the TBRS model (Barrouillet et al., 2004). The task-switching model and the TBRS model (in both its variants) are based on very similar assumptions: Memory traces decay over time unless rehearsed, and rehearsal is not possible during cognitive work on the processing task. Nonetheless, these models make opposite predictions for the effect of processing time when the amount of processing is held constant. The task-switching model predicts that memory declines with longer processing times, because people are assumed to switch to the maintenance task only at the end of a processing sequence; the TBRS model, however, predicts better memory with longer processing times, because it assumes that the cognitive system uses brief pauses in the processing sequence to rehearse memory traces. The interference hypothesis predicts no effect in this case because the duration of processing should not matter as long as the amount of processing is held constant. Our results clearly confirm the predictions of one version of the TBRS model, and they contradict those of the task-switching and interference accounts.

The two versions of TBRS differ in their assumptions about rehearsal. One commonly assumed mechanism of rehearsal of verbal material in working memory is overt or silent articulation. If the rehearsal that is assumed to be squeezed into brief processing pauses relies on articulation, it should be blocked by continuous reading. Experiment 2 confirmed that continuous reading reduced the number of individual syllables that could be articulated in between processing to about one-tenth of those that could be articulated in normal reading conditions. Continuous reading therefore impeded articulatory rehearsal much more efficiently than did normal reading, and it largely reduced the advantage of long- over short-presentation duration with regard to concurrent articulation. Therefore, a version of TBRS assuming only an articulatory rehearsal mechanism must predict an interaction of presentation duration with reading conditions. Such an interaction was not obtained. Memory performance with slower reading improved as much in the continuous reading condition as it did in the normal reading condition. This finding rules out TBRS–a, the version of the time-based resource-sharing model in which rehearsal is based only on subvocal articulation.

We are left with one model, TBRS–r, that can explain all of the present findings. This model assumes that rehearsal is based on a retrieval mechanism that competes with central cognitive processes but can operate concurrently with overt articulation. Longer presentation durations lead to better memory performance because they leave longer pauses in between the demands on the central cognitive operations involved in reading. These pauses can be used for refreshing the memory traces. The advantage of longer presentation durations is as great with continuous as with normal reading, because reading at a slower pace stretches the same amount of central processing operations over a longer time, regardless of whether reading is continuous or not. Continuous reading arguably requires more central processing than does normal reading because it places higher demands on executive control to ensure that reading follows the given beat. However, this is equally true for fast and for slow reading and therefore produces only an additive effect, which is exactly what we found.

Implications for Rehearsal in Working Memory

Taken together, the present results provide compelling evidence for two assumptions of the TBRS–r model as proposed by Barrouillet et al. (2004), both of which concern the role of rehearsal in working memory.

First, memory performance was better with longer than with shorter presentation durations, and this strongly suggests that the cognitive system uses brief pauses in between individual processing steps to somehow strengthen memory traces. We see no alternative explanation for the beneficial effect of slower processing rates, and therefore we find this conclusion hard to avoid. Strengthening the memory trace could simply mean a form of maintenance rehearsal, such as reactivating the existing trace, as assumed by Barrouillet and colleagues, but it could also involve elaborative rehearsal, enriching or reorganizing the existing memory trace or consolidating it in long-term memory. It should be noted that our results do not speak to another assumption of the TBRS model, which is that in the absence of rehearsal, memory traces decay over time. Strengthening the memory trace in between processing steps is advantageous to memory, regardless of which mechanism produces forgetting. We only need to assume that memory traces be degraded during the encoding of further items and the interleaved processing operations—this can happen through decay or through a form of interference during encoding and processing, such as feature overwriting (Nairne, 1990; Oberauer & Kliegl, 2006).

Second, the advantage of a slow versus a fast processing rate was observed even under conditions of continuous reading. This finding implies that the working memory system can operate on its memory traces concurrently with the articulation of sentences. Support for this conclusion comes from an informal postexperimental interview in which participants reported "internal repetition" of the target items as a frequently used strategy. This strategy was reported as often in the normal reading group as in the continuous reading group. These findings are in line with the assumption that memory items are rehearsed or refreshed by what Barrouillet et al. called a central bottleneck—a mechanism that competes with central components of the processing task but not its sensory or motor components. Reading is an activity in which motor execution can last considerably longer than the cognitive processes that presumably require the retrieval bottleneck. The bottleneck would be required for operations such as identification of words, lexical activation, and output planning, but not output production. Therefore, even when overt reading is continuous, cognitive pauses can be used to refresh the memory traces. In our version of the reading span task, the demand on central processes was comparatively low—in particular, there was no need to understand the sentence. Participants probably engaged in a kind of mindless reading that places comparatively few demands on the bottleneck for the processing task. Reading for meaning might recruit the bottleneck more continuously, leaving less opportunity for switching between reading and rehearsal. If this is the case, the advantage of slow over fast processing might be eliminated or reversed when people are required to comprehend the sentences in a reading span task.

If our analysis is correct, we are forced to conclude that there are two mechanisms of rehearsal of verbal information in working memory, one based on silent articulation and the other based on processes of the central bottleneck—the latter could consist of retrieval or of more elaborate processes serving to protect memory representations from forgetting. The possibility of two forms of rehearsal was anticipated early in the development of working memory research (Vallar & Baddeley, 1982), but the evidence for it was not compelling, and it was therefore largely neglected. One exception is the distinction made between rehearsal and refreshing in the MEM framework of Johnson (1992). In this framework, *rehearsal* refers to subvocal rearticulation, whereas *refreshing* refers to reactivating a memory representation. Evidence for a dissociation of the two mechanisms has been obtained through fMRI studies (Raye, Johnson, Mitchell, Reeder, & Greene, 2002), showing that refreshing recruits dorsolateral prefrontal cortex, whereas articulatory rehearsal recruits speech-related cortical regions, such as Broca's area and premotor cortex (Smith & Jonides, 1997).

Implications for Theories of Forgetting in Working Memory

Our conclusion that working memory can use two kinds of rehearsal for verbal material has several implications that require a reevaluation of previous research bearing on the role of time for forgetting in working memory. Both proponents and opponents of time-based decay have usually regarded articulatory rehearsal as the only form of trace reactivation; preventing it would therefore leave memory traces to decay. Research in the tradition of Baddeley's (1986) model has relied on this assumption for the interpretation of countless findings involving articulatory suppression and the word length effect. Articulatory suppression is assumed to impair serial-order memory because it blocks rehearsal and therefore leaves representations to decay. If rehearsal is possible concurrently with articulation, however, this assumption becomes questionable. We may have to reinterpret the effects of articulatory suppression in terms of an interference account: Interference due to the generation of irrelevant phonological representation (Neath & Nairne, 1995) or due to irrelevant order information (Jones, Beaman, & Macken, 1996), rather than disruption of subvocal rehearsal, might be responsible for the detrimental effect of articulatory suppression on short-term retention.

Likewise, the word length effect (Baddeley, Thomson, & Buchanan, 1975) is commonly interpreted as arising from longer decay times during the articulation of longer words during rehearsal or recall. The decay interpretation can be made most forcefully when the words are selected in such a way that they differ only in the time needed to pronounce them, and other factors that might affect their processing difficulty are controlled (see, e.g., Mueller, Seymour, Kieras, & Meyer, 2003). When words differ only in their pronunciation time, however, they most likely place the same demand on a cognitive bottleneck and differ only in the amount of time they require for motor output. The opportunity for retrieval-based rehearsal, therefore, should not differ for long and short words; consequently, there is not even a convincing basis on which a decay account predicts the word-length effect. In fact, the TBRS–r model could be used to predict better recall of longer words, because their articulation involves a smaller cognitive load (i.e., a smaller ratio of word retrievals to total processing time). The decay interpretation of the word length effect has already come under repeated attack because the effect is fraught with confounds that give rise to alternative explanations (see, e.g., Brown & Hulme, 1995; Lovatt, Avons, & Masterson, 2000; Service, 1998; for a defense, see Mueller et al., 2003). With clear evidence for a rehearsal mechanism that can operate independently of articulation, there is no clear support for a decay account of the word length effect. This conclusion strengthens alternative accounts of the word length effect that do not assume decay or rehearsal (Neath & Nairne, 1995).

Critics of time-based decay, however, face a related problem. Demonstrations that memory performance is unaffected by the passage of time are strong evidence against decay only if researchers can make sure that the information to be remembered is not rehearsed. The strongest case against time as a factor in forgetting within working memory has been made by Lewandowsky, Duncan, and Brown (2004) and Nimmo and Lewandowsky (2005). They showed that the length of a time interval between list items during encoding or during recall did not affect recall performance, even if participants were required to engage in an irrelevant articulation task during these pauses. The articulation task is arguably sufficient to block articulatory rehearsal, but our findings suggest that it is not sufficient to block retrieval-based rehearsal. Therefore, participants in the studies of Lewandowsky et al. and Nimmo and Lewandowsky might still have used the pauses to rehearse list elements, thereby preventing decay. In conclusion, our findings make the lives of both proponents and critics of decay harder, because an experimental demonstration of decay or of its absence with verbal material requires the blocking of both rehearsal mechanisms.

There is still one question to be discussed: Why do our results differ from those of Saito and Miyake (2004) in their Experiments 4A and 4B, given that our experimental paradigm was very similar to theirs? An important difference between our paradigm and that of Saito and Miyake is the way in which processing time was manipulated. Whereas we divided all sentences into four segments and manipulated their presentation durations, Saito and Miyake held the presentation duration of individual segments constant and created longer overall duration by dividing sentences into more and smaller segments. In terms of Barrouillet et al. (2004), both manipulations should have induced a lighter cognitive load, because the same amount of material was spread over a longer time. The advantage of a lighter load derives from the opportunity it provides for switching the retrieval bottleneck away from the processing task to the task of refreshing the memory items. The technique used by Saito and Miyake to increase processing duration might have created few opportunities for switching away from the reading task, because it forced participants to divide their speech-planning process into smaller episodes.

Let us assume, in line with our argument stated previously, that the bottleneck is required for planning speech output, but not for actual articulation. Let us further assume that people plan the articulation of a whole segment as soon as the segment appears on the screen, and then use the time before the next segment appears for rehearsal. A long-duration sentence in Saito and Miyake's experiments would thus involve more time overall for rehearsal than would a short-duration sentence, but rehearsal would be interrupted more often by the appearance of a new segment. Within each segment, there would be roughly equally long intervals for uninterrupted rehearsal. As a consequence, the benefit of having a long-duration sentence toward the end of the list might have been very small in Saito and Miyake's Experiments 4A and 4B, and this could explain why they did not find a difference in memory performance between conditions that formally differed in cognitive load as defined by Barrouillet (2004).

CONCLUSION

The present study evaluated four models of forgetting in working memory. The results favor the TBRS model, since shorter processing times led to worse recall than did longer processing times. In particular, the results support the version of TBRS that assumes a rehearsal mechanism independent of articulation. The findings directly contradict the prediction of the task-switching model as introduced by Towse et al. (1998, 2000), but it should be noted that the TBRS model is conceptually very similar to the original task-switching model, in that it is based on trace decay and rapid switching between processing and rehearsal. Our results pose a challenge for the representational interference account as proposed by Saito and Miyake (2004), but they do not rule out interference as one (possibly the only) source of forgetting. Representational interference could replace decay as the mechanism of forgetting in the TBRS–r model. An interference model augmented by the rehearsal assumptions of TBRS–r is thus a viable explanation of our findings.

Our findings help to clarify the nature of rehearsal in working memory. Besides articulatory rehearsal, there is a second process that strengthens or protects memory traces. This process competes for time on a bottleneck with other central cognitive processes, but it can operate concurrently with motor processes (including speech production). The idea of a retrieval bottleneck as invoked by Barrouillet et al. (2004) is closely related to the central bottleneck as conceived in the literature on attention and action (Pashler et al., 2000). We regard this link as an invitation to integrate two fields of research on human capacity limits that have been largely separated in the past: the investigation of working memory capacity and the study of attentional limits on parallel processing (cf. Oberauer & Göthe, 2006).

AUTHOR NOTE

This work was supported by Grant OB 121/3-3 of Deutsche Forschungsgemeinschaft. We thank Pierre Barrouillet, Reinhold Kliegl, Elke Lange, Katrin Göthe, and Akira Miyake for helpful comments on this work. Correspondence concerning this article should be addressed to A. Hudjetz, University of Potsdam, Allgemeine Psychologie 1, Karl-Liebknecht-Str. 24–25, 14476 Potsdam OT Golm, Germany (e-mail: annekatrin.hudjetz @uni-potsdam.de).

REFERENCES

BADDELEY, A. [D.] (1986). *Working memory*. Oxford: Oxford University Press, Clarendon Press.

BADDELEY, A. D., & HITCH, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47-90). New York: Academic Press.

BADDELEY, A. D., THOMSON, N., & BUCHANAN, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning & Verbal Behavior*, **14**, 575-589.

BARROUILLET, P., BERNARDIN, S., & CAMOS, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, **133**, 83-100.

BARROUILLET, P., & CAMOS, V. (2001). Developmental increase in working memory span: Resource sharing or temporal decay? *Journal of Memory & Language*, **45**, 1-20.

Brown, G. D. A., & Hulme, C. (1995). Modeling item length effects in memory span: No rehearsal needed? *Journal of Memory & Language*, **34**, 594-621.

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review*, **12**, 769-786.

Cowan, N. (1995). *Attention and memory: An integrated framework*. New York: Oxford University Press.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning & Verbal Behavior*, **19**, 450-466.

Hitch, G., Towse, J. N., & Hutton, U. (2001). What limits children's working memory span? Theoretical accounts and applications for scholastic development. *Journal of Experimental Psychology: General*, **130**, 184-198.

Johnson, M. K. (1992). MEM: Mechanisms of recollection. *Journal of Cognitive Neuroscience*, **4**, 268-280.

Jones, D. M., Beaman, P., & Macken, W. J. (1996). The object-oriented episodic record model. In S. E. Gathercole (Ed.), *Models of short-term memory* (pp. 209-238). Hove, U.K.: Psychology Press.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity?! *Intelligence*, **14**, 389-433.

Lewandowsky, S., Duncan, M., & Brown, G. D. A. (2004). Time does not cause forgetting in short-term serial recall. *Psychonomic Bulletin & Review*, **11**, 771-790.

Lovatt, P., Avons, S. E., & Masterson, J. (2000). The word-length effect and disyllabic words. *Quarterly Journal of Experimental Psychology*, **53A**, 1-22.

Mueller, S. T., Seymour, T. L., Kieras, D. E., & Meyer, D. E. (2003). Theoretical implications of articulatory duration, phonological similarity, and phonological complexity in verbal working memory. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **29**, 1353-1380.

Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition*, **18**, 251-269.

Neath, I., & Nairne, J. S. (1995). Word-length effects in immediate memory: Overwriting trace decay theory. *Psychonomic Bulletin & Review*, **2**, 429-441.

Nimmo, L. M., & Lewandowsky, S. (2005). From brief gaps to very long pauses: Temporal isolation does not benefit serial recall. *Psychonomic Bulletin & Review*, **12**, 999-1004.

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **28**, 411-421.

Oberauer, K., & Göthe, K. (2006). Dual-task effects in working memory: Interference between two processing tasks, between two memory demands, and between storage and processing. *European Journal of Cognitive Psychology*, **18**, 493-519.

Oberauer, K., & Kliegl, R. (2006). A formal model of capacity limits in working memory. *Journal of Memory & Language*, **55**, 601-626.

Pashler, H., Johnston, J. C., & Ruthruff, E. (2000). Attention and performance. *Annual Review of Psychology*, **52**, 629-651.

Raye, C. L., Johnson, M. K., Mitchell, K. J., Reeder, J. A., & Greene, E. J. (2002). Neuroimaging a single thought: Dorsolateral PFC activity associated with refreshing just-activated information. *NeuroImage*, **15**, 447-453.

Saito, S., & Miyake, A. (2004). On the nature of forgetting and the processing–storage relationship in reading span performance. *Journal of Memory & Language*, **50**, 425-443.

Service, E. (1998). The effect of word length on immediate serial recall depends on phonological complexity, not articulatory duration. *Quarterly Journal of Experimental Psychology*, **51A**, 283-304.

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology*, **33**, 5-42.

Süß, H.-M., Oberauer, K., Wittmann, W. W., Wilhelm, O., & Schulze, R. (2002). Working-memory capacity explains reasoning ability—and a little bit more. *Intelligence*, **30**, 261-288.

Towse, J. N., Hitch, G. J., & Hutton, U. (1998). A reevaluation of working memory capacity in children. *Journal of Memory & Language*, **39**, 195-217.

Towse, J. N., Hitch, G. J., & Hutton, U. (2000). On the interpretation of working memory spans in adults. *Memory & Cognition*, **28**, 341-348.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory & Language*, **28**, 127-154.

Vallar, G., & Baddeley, A. D. (1982). Short-term forgetting and the articulatory loop. *Quarterly Journal of Experimental Psychology*, **34A**, 53-60.

(Manuscript received May 12, 2006;
revision accepted for publication October 16, 2006.)