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Minding the load or loading the mind: The effect of manipulating working memory on coherence monitoring

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ABSTRACT

Working memory plays an important role in complex cognitive tasks. For example, in the context of reading, it has been argued that working memory provides a workspace for maintenance and integration of different text units and relevant background knowledge. However, the amount of information that needs to held in mind is often at odds with the very restricted capacity traditionally posited by models of working memory. Moreover, direct evidence concerning the role of working memory during reading is ambiguous and largely based on correlational studies. To address these issues, we conducted two dual-task studies in which we manipulated working memory capacity during reading, and examined the effects of working memory capacity on the processes (rather than the products) of reading comprehension. Both experiments focused specifically on the process of coherence monitoring, a crucial component of comprehension, by comparing participants' responses (i.e., reading times) for texts with and without inconsistencies. Moreover, in Experiment 2 we additionally examined the interaction between working memory load and availability of information by varying textual distance between inconsistent sentences. Both experiments showed that the external working memory load interfered with coherence monitoring, as reflected by reduced responses to inconsistencies. Experiment 2 further revealed that, in addition to working memory capacity, coherence monitoring is influenced by availability. Interestingly, the effect of availability was only significant in the no-load conditions, suggesting that load reduces the inconsistency effect regardless of availability. Together, these findings suggest that although readers may progress through a text relatively effortlessly by using activated portions of long-term memory, the process of coherence monitoring requires at least some working memory capacity.

Introduction

Life constantly requires us to manage, compare, and combine large amounts of information. This is evident in complex activities such as designing a prototype for a model airplane or creating a week-to-week outline for a college course, but also in more every day contexts such as reading, math-problem solving, or following a recipe. For example, in the context of reading, understanding written text involves visual processing of letters and combining them into words, matching words to their phonological and semantic representations in long-term memory, and integrating different text units with each other and with the reader's background knowledge into a mental representation of the text (Perfetti, Yang, & Schmalhofer, 2008; Johnson-Laird, 1983; Kintsch, 1988). These processes are often thought to take place in working memory, which is generally defined as a short-term, limited-capacity memory system of components responsible for the storage and processing of information (Baddeley, 1986, 2000; Baddeley & Hitch, 1974; Daneman & Carpenter, 1980; Cowan, 2017). Not surprisingly, therefore, working memory has long been argued to play a central role in reading comprehension (Just & Carpenter, 1992; Daneman & Carpenter, 1980; Wylie, Thomson, Leppänen, Ackerman, Kanniainen, & Prieler, 2018).

However, the role of working memory during reading comprehension might be smaller than is frequently argued. Skilled readers often proceed relatively effortlessly through a text, particularly when the text is well-written and involves a familiar topic (Ericsson & Kintsch, 1995). Therefore, as is the case with processing well-known visual material and oral language, processing textual information that fits smoothly into existing knowledge structures probably does not place a large demand on working memory capacity (Adams, Nguyen, & Cowan, 2018). This may explain recent findings suggesting that the observed relation between working memory capacity and reading comprehension disappears when controlling for other factors that may influence processing

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difficulty, including decoding skills, vocabulary, and IQ (Peng et al., 2018; Van Dyke, Johns, & Kukona, 2014; Freed, Hamilton, & Long, 2017). Nevertheless, working memory may still be required for more complex reading comprehension processes. In the present study, we investigate this possibility with respect to an important component of reading comprehension, namely monitoring coherence during reading.

Working memory and reading comprehension

Working memory is often described as a system of cognitive components responsible for temporarily holding a limited amount of information in a heightened state of availability to be used in ongoing processing (Cowan, 2017). Although most working memory researchers agree on this generic definition of working memory, there is no complete consensus about the operationalisation of this idea, with models and theories varying in the details of (sub)processes involved in working memory (see Cowan, 2017 for an overview of definitions). One important aspect on which models of working memory vary is the extent of interaction between working memory and long-term memory they postulate (see Adams, Nguyen, & Cowan, 2018 for an overview); some models strictly separate working memory from long-term memory (e.g., Atkinson & Shiffrin, 1968; Jeneson & Squire, 2012), whereas other models posit more reciprocity or even overlap between working memory and long-term memory (e.g., Cowan, 1988, 1999, 2001; Ericsson & Kintsch, 1995; Oberauer, 2009; Adams, Nguyen, & Cowan, 2018). Because reading for comprehension draws heavily on the reader's background knowledge (i.e., long-term memory), in this study we adopt a framework that emphasizes the interaction between working memory and long-term memory, based on the embedded-processes model (Cowan, 1988, 1999, 2001; Adams, Nguyen, & Cowan, 2018) and the long-term working memory framework (Ericsson & Kintsch, 1995).

The embedded-processes model (Cowan, 1988, 1999, 2001; Adams, Nguyen, & Cowan, 2018) differentiates between an activated portion of long-term memory that allows information to stay in a heightened state of availability and a focus of attention with limited capacity in which a subset of this information is kept. Although Cowan and colleagues initially assumed that most information that is needed for processing would remain in the focus of attention (Cowan, 1988, 1999, 2001), more recently they suggest that information is often quickly off-loaded to the activated portion of long-term memory, thereby freeing up resources for processing other information (Adams, Nguyen, & Cowan, 2018). A similar idea is put forward by Ericsson and Kintsch (1995), who propose two different *types* of working memory: a short-term working memory and a long-term working memory. Short-term working memory is available under all conditions, but is severely limited in its capacity (akin to Cowan's focus of attention). Long-term working memory, in contrast, has no limited capacity but is only available in well-established knowledge domains or skills (such as reading). As in the embedded process model, long-term working memory is proposed to consist of an activated subset of long-term memory that is directly retrievable via cues in short-term working memory.

The embedded process model and the long-term working memory framework complement models of reading comprehension, which generally assume that the content of incoming information triggers an automatic and unrestricted spread of activation through the memory of a reader (Kintsch, 1988; McKoon & Ratcliff, 1992; Cook & O'Brien, 2014; Smith & O'Brien, 2016). This spread of activation can explain how readers are able to comprehend (simple) texts relatively effortlessly and how they are able to keep more information available than would be expected based on the proposed capacity limits of working memory. Take, for example, the following sentences "*The clown approached Julia. In his hand was a balloon animal. Julia ran away crying.*". The focus of attention briefly holds the concept 'clown', which activates existing knowledge structures within long-term memory containing the properties of the concept, such as 'red nose', 'jokes', and 'may scare children'. As a result of these activated representations one can relatively effortlessly understand that Julia runs away because she is scared of the clown. In other words, the incoming information can be easily integrated with existing knowledge structures and therefore will not put large demands on working memory capacity[i]. However, a different scenario emerges when the establishment of coherence is not so easy or when there is a break in coherence. Then, further processing often is required.

Coherence monitoring

Most models of reading comprehension agree that the formation of a coherent mental representation, or situation model, of the text by the reader is central to successful reading comprehension (Kintsch & Van Dijk, 1978; Gernsbacher et al., 1990; Graesser, Singer, & Trabasso, 1994; Zwaan, Magliano, & Graesser, 1995; Van den Broek, Young, Tzeng, & Linderholm, 1999). To build an internally-consistent situation model, incoming information must be integrated with and validated against the activated representation of the prior text and the background knowledge of the reader (Singer, 2013; Kendeou, 2014; Van Moort, Koornneef & Van den Broek, 2018). If readers encounter information that is inconsistent, coherence is disrupted. The process of coherence monitoring, particularly the detection of (in)coherence, has been investigated experimentally using a contradiction paradigm (Albrecht & O'Brien, 1993; Cook, Halleran, & O'Brien, 1998; O'Brien & Albrecht, 1992). In this paradigm participants read short narratives, including narratives that contain a target sentence that semantically contradicts information presented earlier in the story. For example, a main character, Mary, is introduced as a vegetarian in the beginning of the story but, after a few filler sentences, readers encounter a sentence in which Mary orders a hamburger. Such contradictions cause breaks in coherence. When reading times for the target sentences from consistent narratives are compared to those from narratives with inconsistencies, readers usually show an *inconsistency effect*: processing inconsistent target sentences takes more time than processing consistent target sentences. Thus, differences in observed reading times reflect online detection of coherence breaks. Whether a coherence break is detected during reading depends on the availability of the to-be-compared information and on the integration and validation processes that are used to compare the different pieces of information (Cook & O'Brien, 2014; Isberner & Richter, 2014; Kintsch, 1988; Van den Broek & Kendeou, 2008). These coherence monitoring processes may take effort and place demands on working memory capacity (Oakhill, Hartt, & Samols, 2005; Currie et al., 2020). Alternatively, monitoring processes may be carried out routinely and require relatively little working memory capacity because they rely on information that is easily accessible through activated long-term memory (Schroeder, Richter, & Hoever, 2008; McKoon & Ratcliff, 1992), allowing for simple pattern matching (Smith & O'Brien, 2016). In the current study we differentiate between these two possibilities using a contradiction paradigm that is administered in the context of a dual-task situation.

The current study

The current study is certainly not the first to examine the relation between working memory capacity and reading, but the results so far have been mixed. In some studies, working memory almost fully explained reading performance, with R^2 values ranging from .60 to .81 (e.g., Daneman, 1991; Weissinger, 2013; McIntyre, 2015), while other studies found only trivial contributions of working memory to reading, with R^2 values around 0 (e.g., Koltum, 2003; O'Shaughnessy & Swanson, 2000). Interestingly, Peng et al. (2018) found no significant relation

[i] In this paper the term working memory capacity corresponds to the focus of attention in the embedded processes model or the short-term working memory in the long-term working memory framework of Ericsson and Kintsch (1995).

between working memory capacity and reading comprehension in their meta-analysis when controlling for decoding and vocabulary. Similarly, several studies have suggested that reported relations between working memory capacity and reading are spurious and likely due to the overlap between working memory measures and other reading-related measures, especially IQ and general reasoning (Van Dyke, Johns, & Kukona, 2014; Freed, Hamilton, & Long, 2017). Complicating conclusions about the role of working memory capacity in reading comprehension further, prior studies often relied on *offline* products of reading comprehension (i.e., performances on recall or comprehension questions). Such measures only indirectly implicate the nature of the underlying online processes. Moreover, it would be possible for working memory capacity to influence online reading processes without the effects becoming visible in traditional tasks that measure the offline product of reading comprehension. For example, the results of the Baddeley and Hitch studies (1974) showed that in dual-task situations the comprehension of texts (i.e., the offline product) is relatively unaffected by memory load (up to six digits) presented during reading.

To investigate the possible role of working memory capacity in coherence monitoring while addressing the abovementioned issues, we experimentally manipulated working memory capacity *during* reading using a dual-task design. Specifically, we used the contradiction paradigm (O'Brien & Albrecht, 1992) to observe *online* coherence monitoring, and manipulated working memory capacity by adding a secondary task to load working memory capacity. Participants read consistent and inconsistent stories from a computer, sentence-by-sentence. In the load condition, participants were also instructed to remember (random) digits that were presented between the sentences. After each story participants answered a comprehension question and, in the load condition, recalled as many digits as they could remember.

This design allowed us to test two possible scenarios concerning the potential role of working memory capacity in coherence monitoring. The first scenario assumes that coherence monitoring is an effortless and relatively automatic process (e.g., Schroeder, Richter, & Hoever, 2008; Smith & O'Brien, 2016). In this scenario, the automatic and unrestricted spread of activation through a reader's background knowledge leads to co-activation of potentially conflicting pieces of information in the activated portions of long-term memory and this co-activation is sufficient for the detection of an inconsistency, for example by allowing simple pattern matching (Smith & O'Brien, 2016). If this is the case, one would expect to find longer reading times of the target sentences for inconsistent stories than for consistent stories regardless of whether there was a load or not.

The second scenario, in contrast, assumes that coherence monitoring is an effortful process and requires the relevant information to be held within working memory (Oakhill, Hartt, & Samols, 2005; Currie et al., 2020). In this scenario, the activation of long-term memory following the automatic and unrestricted spread of activation alone is not sufficient to detect an inconsistency. If this is the case, the required processes would be compromised by a working memory load and therefore we would expect an interaction between consistency and load, with a stronger inconsistency effect in the no-load than the load condition.

Experiment 1

Method

Participants

In total 41 participants were included in this study (30 women, 11 men). Their ages ranged between 18 and 30 years ($M = 22.68$, $SD = 3.17$). All participants were undergraduate students who signed up through the Leiden University Research Participation System. For their participation they received course credits or money. Participants with a diagnosis of dyslexia or developmental disorders (e.g. ADHD or Autism-Spectrum Disorders) and non-native Dutch-speakers were excluded.

Table 1
Example of a story.

Introduction sentence	Mia takes home a friend for a play date
Context sentence	*Mia lives in a house with a big garden (consistent)* *Mia lives on the 6th floor and doesn't have a garden (inconsistent)*
Filler	Mia's mother helps the girls to bake cookies
Filler	They put some extra chocolate in some of them
Filler	After 20 min in the oven, the cookies are done
Target sentence	**Together they enjoy the cookies in the garden**
Comprehension question	Mia's mother helped them make a cake – NO

Materials

Reading task. Participants read 64[ii] narrative stories adapted from O'Brien and colleagues (O'Brien & Albrecht, 1992; O'Brien, Rizzella, Albrecht & Halleran, 1998). The stories were presented one sentence at a time on a computer screen. Each story consisted of six sentences: an introductory sentence, a sentence that described a characteristic of a person or situation, three filler sentences, and a target sentence. All sentences consisted of approximately 10 words ($M = 9.52$, $SD = 2.18$). By manipulating the content of the second sentence we created two versions for each story: (a) a version in which the information of the second sentence was consistent with the information in the target sentence, and (b) a version in which the information of the second sentence was contradicting the information in the target sentence. The target sentence was identical between the two versions of each story, and varied between 7 and 16 words across stories ($M = 11.20$, $SD = 2.22$). For an example of the stories see Table 1 (for a translation of the context sentences and the target sentences of all stories, see Appendix A).

To make sure the inconsistencies would work 62 students rated the inconsistencies in all 64 stories on a five-point Likert scale: *very strongly inconsistent (1) – strongly inconsistent (2) – somewhat inconsistent (3) – weakly inconsistent (4) – very weakly inconsistent (5)*. The majority of the students rated 55 stories as (very) inconsistent. Only 4 stories were ranked as (very) weak inconsistent by the majority of the students. The average inconsistency for all stories was 1.91, corresponding to *strongly inconsistent.*

Half of the stories were read in a no-load condition, in which participants read the stories normally. The other half was read in a load condition, in which participants were instructed to remember 6 digits that were presented during reading of the stories. The no-load condition and load condition were presented in different blocks, each including 16 consistent and 16 inconsistent stories. We used a Latin square to construct two lists; each of the 64 stories appeared in a different version (consistent or inconsistent) on each list. Each participant read one version of each story, with the order in which the stories were presented randomized.

Participants read each story sentence-by-sentence on a computer screen, pressing the spacebar to advance to the next sentence. This allowed us to analyse reading times for each sentence separately. After each sentence a digit was presented for 1000 ms. In the load condition, participants were instructed to keep these digits in mind and report them back after the story. In the no-load condition, participants were instructed to ignore the digits. Following each story participants answered a comprehension question about the content of the story with a 'yes' or 'no' button press (using the '1' and '2' keys on the number pad of the keyboard, respectively). In the load condition participants were then prompted to recall all 6 numbers in the presented order. Participants could type the digits in an input box. Before continuing to the next story, a fixation cross was presented for 500 ms. After the reading task, participants completed an exit questionnaire consisting of questions to

[ii] We based the size of our sample on Brysbaert & Stevens (2018) who recommend a minimum of 1,600 observations per condition in designs with repeated measures. We have 2.624 observations (41 participants x 64 stories).

Table 2
The mean reading times and standard deviations in ms. as a function of condition (load vs. no-load) and consistency (consistent vs inconsistent).

	Consistent		Inconsistent	
	M	*SD*	*M*	*SD*
No-load	1912	954	2251	1162
Load	4143	2342	4323	2492

assess their motivation, use of strategies, and relative focus on comprehending the stories versus on recall of the digits.

Procedure

All participants were tested individually in one of the labs at Leiden University. At the beginning of the session they signed informed consent forms. Participants started with the reading task. They were instructed to read the stories carefully and answer questions about them. In the load condition an additional instruction was given: to remember as many digits as possible. After the instructions, participants practiced with an example story to make sure they understood the instructions and to familiarize themselves with the sentence-by-sentence reading. During this practice trial the participants received feedback. After the practice trial, participants completed two blocks of stories (a no-load and a load block) separated by new instructions and a practice trial. When participants completed the reading task an exit questionnaire was administered. Each testing session lasted about an hour.

Results

Comprehension questions and digit recall

Before analysing the reading time data, the responses to the comprehension questions and the number of correctly recalled digits were inspected. On average, participants answered 88% of the comprehension questions correctly in the no-load condition ($SD = 6.9\%$) and 85% in the load condition ($SD = 8.6\%$). In the load condition, participant remembered on average 5.3 of the 6 digits correctly ($SD = 0.58$). These scores indicate that participants were paying attention to the stories and, in the load condition, also to the digits.

Reading times

Extremely short or long reading times on the target sentence (shorter than 700 ms or longer than 12,218 ms, corresponding to the highest and lowest 1%) were excluded from the analyses. Table 2 reports the means and standard deviations of the resulting reading times as a function of condition (no-load/load) and consistency (consistent/inconsistent). We log-transformed the reading times of the target sentence because they were skewed to the right. Subsequently, linear mixed effects models (LMEMs) were fitted with the R-package LME4 (version 1.1–21) to test the main and interaction effects of the factors condition and consistency. Participants and items were included as crossed random effects. Two models were fitted. One model contained random intercepts only. To avoid Type I statistical errors, the results were verified with an LMEM that included the maximal random effect structure (see Barr, Levy, Scheepers, & Tily, 2013; Bates, Kliegl, Vasishth, & Baayen, 2015, and Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017 for a discussion on maximal vs. parsimonious mixed models).

We will report the results for the random-intercept-only model and indicate where the results of the models diverge (this was not the case in Experiment 1; see Appendix B for details of the maximal LMEM and note that the inclusion of random slopes resulted in a singular fit). We report both the results of Wald tests (in tables) and the estimates of the fixed effects (in the text). We used the R-package EMMEANS (version 1.5.1) to extract the fixed effects estimates and conduct the pairwise comparisons that were licenced by the output of the model. Kenward-Roger approximations were used to compute the degrees of freedom (df) for these (follow-up) analyses. In all analyses, effects were classified as significant when $p < .05$.

Table 3
Wald tests of the model for the log-transformed reading times on the target sentences. The following R code was used: log(reading time) ~ 1 + condition * consistency + (1 | subject) + (1 | item).

Wald test	χ2	Df	P
Condition	1685.75	1	< 0.001*
Consistency	29.08	1	< 0.001*
Condition*Consistency	12.63	1	< 0.01*

The results of the Wald tests revealed significant main effects for the factors condition and consistency, and a significant condition by consistency interaction (see Table 3). The reading times in the load condition were longer than the reading times in the no-load condition ($\widehat{\beta} = 0.67$, SE = 0.016, df = 2439, $t = 41.06$, $p < .0001$). Furthermore, reading times were longer for inconsistent targets than for consistent targets ($\widehat{\beta} = -0.088$, SE = 0.016, df = 2438, $t = -5.37$, $p < .0001$).

Follow-up analyses of the significant condition by consistency interaction revealed that the inconsistency effect was larger in the no-load condition than in the load condition ($\widehat{\beta} = 0.12$, SE = 0.033, df = 2432, $t = 3.55$, $p < .001$). More specifically (illustrated in Fig. 1), the inconsistency effect was significant in the no-load condition ($\widehat{\beta} = -0.15$, SE = 0.023, df = 2436, $t = -6.33$, $p < .0001$) but not significant in the load condition ($\widehat{\beta} = -0.030$, SE = 0.023, df = 2435, $t = -1.29$, $p = .20$).

Discussion Experiment 1

To examine possible effects of working memory capacity on coherence monitoring, a central component of reading comprehension, we manipulated working memory load during reading. The results showed that imposing a working memory load did interfere with coherence monitoring, as reflected in a reduced detection of inconsistencies. Hence, the results support the hypothesis that coherence monitoring is, at least in part, an effortful process, requiring working memory capacity.

There are several possible interpretations of the observed effect of load. First, the effect may have occurred because the relevant information was too 'far' away in activated long-term memory and therefore not accessible under conditions of high load. Second, it is possible that there simply was not enough capacity for the integration of two conflicting sources of information, irrespective of the strength of available information. Models on reading comprehension (implicitly) divide coherence monitoring into at least two steps (Kintsch, 1988; Myers & O'Brien, 1998; Van den Broek et al., 1999). The first step, making the information available, is likely accomplished through passive retrieval. This process is described as *spread of activation* (Kintsch, 1988), *resonance* (Myers & O'Brien, 1998), or *cohort activation* (Van den Broek et al., 1999) and operates on pre-existing knowledge structures. The availability of information in this passive retrieval process depends on both the recency that the information has been encountered, and on its association with information that is currently in working memory (Smith & O'Brien, 2016; Van den Broek, Young, Tzeng & Linderholm, 1999; Tzeng, Van Den Broek, Kendeou, & Lee, 2005). The second step refers to the processing of the activated relevant information, often described as *integration* or *validation* (Singer, 2013; Kendeou, 2014; Van Moort et al., 2018). Whereas it is quite plausible that external working memory load reduces the capacity for integration and validation processes, it is less obvious whether the availability of information plays a role in this effect. To explore this question, we conducted a second experiment in which we manipulated the distance between the context sentences and the target sentences. Reducing the textual distance between context and target makes the relevant information more available (Barth, Barnes, Francis, Vaughn & York, 2015; Long & Chong, 2001) and thus potentially diminishes interference from an external working memory load. If this is the case, one would expect a stronger inconsistency effect for

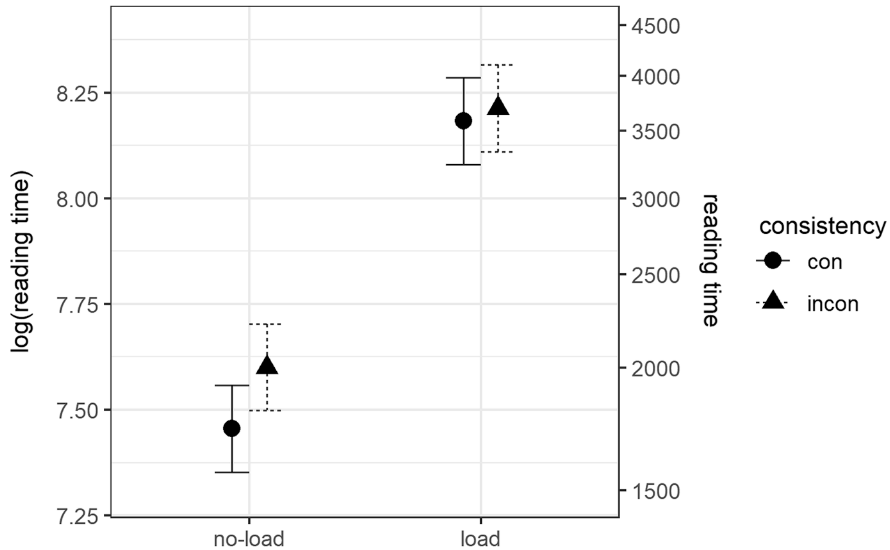

Fig. 1. Mean reading times on consistent and inconsistent target sentences in the no-load and load condition.

stories where the target sentence directly follows the conflicting context sentence ('close' distance) than for stories where the target sentence and the context sentence are far apart ('far' distance). In other words, the effect of load would be reduced at the close distance. Alternatively, external working memory demands may interfere with information entering the focus of attention, regardless of the availability of this information. If this is the case, one would not expect a difference between close and far distance in the load condition, even if there is an effect of distance in the no-load condition.

A secondary aim of Experiment 2 was to control for an alternative explanation for the results of Experiment 1, namely that the reduced inconsistency effect is a result of task-switching and not of working memory load per se. This alternative explanation would run as follows. In the no-load condition of Experiment 1, participants may simply have ignored the digits as they had no instructions to do anything with the digits. In the load condition, in contrast, participants had to switch constantly between the digit task and the reading task. Therefore, an alternative explanation for our findings would be that the continuous task-switching in the load condition interferes with building a coherent mental representation because of repeated redirecting of the focus of attention (i.e., executive control), rather than filling up the capacity of the focus of attention itself. To disentangle the respective influences of working memory capacity and executive control on coherence monitoring we added a switching condition. In this condition, participants saw consonants between the sentences of a text, and they were asked to indicate whether the consonant rhymed with the Dutch word for 'sea' (*zee*). This manipulation involves continuous task-switching (i.e., switching between reading and the rhyme-task) and therefore requires executive control, but it does not require participants to hold the consonants in mind (i.e., does not pose a load on working memory capacity). If task-switching was predominantly responsible for the failure to detect inconsistencies in Experiment 1 one would expect the switch condition to behave similarly as the load condition. In contrast, if working memory capacity constraints were predominantly responsible for the failure to detect inconsistencies, one would expect the switch condition to behave similarly as the no-load baseline condition. In summary, Experiment 2 aims to elucidate whether availability of information plays a role in the effect of working memory load on coherence monitoring and to differentiate between capacity constraints versus executive control demands.

Experiment 2

Method

Participants

In total 161 participants were included in this study (96 women, 65 men). The ages ranged between 18 and 35 years of age ($M = 23.74$, $SD = 2.21$). The educational level of the participants ranged between vocational higher education ($N = 25$), professional higher education ($N = 77$), and university ($N = 59$). Participants with a diagnosis of dyslexia or developmental disorders (e.g. ADHD or Autism-Spectrum Disorders), and non-native Dutch-speakers were excluded. Informed consent was obtained for all participants prior to testing and all procedures were approved by the Leiden University Institute of Education and Child Studies ethics committee.

Materials

Reading task. Participants read 32[iii] narrative stories adapted from O'Brien and colleagues (O'Brien & Albrecht, 1992; O'Brien, Rizzella, Albrecht & Halleran, 1998). These 32 stories were randomly selected from the 64 stories of Experiment 1 (Similar to Experiment 1 the average inconsistency for these 32 stories was strongly inconsistent − 1.88). The stories were presented one sentence at a time on a computer screen. Each story consisted of six sentences: an introductory sentence, a sentence that described a characteristic of a person or situation (context sentence), three filler sentences, and a target sentence. All sentences consisted of approximately 10 words ($M = 9.91$, $SD = 3.42$). By manipulating the content of the context sentence we created two versions for each story: (a) a version in which the information of the context sentence was consistent with the information in the target sentence, and (b) a version in which the information of the context sentence was contradicting the information in the target sentence. The target sentence

[iii] We based our sample on Brysbaert & Stevens (2018) who recommend a minimum of 1.600 observations per condition in designs with repeated measures to interpret differences of approximately 15 ms. In Experiment 2 we have 1.984 observations in the no-load condition (62 participants, 32 stories), 1.696 observations in the load condition (53 participants, 32 stories), and 1.472 observations in the switch condition (46 participants, 32 stories).

Table 4
Example story (close distance).

Introduction	Mia takes home a friend for a play date
Filler	Mia's mother helps the girls to bake cookies
Filler	They put some extra chocolate in some of them
Filler	After 20 min in the oven, the cookies are done
Context	*Mia lives in a house with a big garden (consistent)*
	Mia lives on the 6th floor and doesn't have a garden (inconsistent)
Target	**Together they enjoy the cookies in the garden**
Comprehension question	Mia's mother helped them make a cake – NO

was identical between the two versions of each story, and varied between 7 and 15 words across stories ($M = 11.50$, $SD = 2.13$). We also manipulated the distance between the context sentence and the target sentence. The context sentence was either the second sentence (same as in Experiment 1 – 'far' distance, see Table 1) or the fifth sentence (directly preceding the target sentence – 'close' distance, see Table 4). Participants were assigned to one of three conditions: a) the no-load condition (N = 62), in which participants read the stories normally, b) the load condition (N = 53), in which participants were instructed to remember 6 consonants, instead of digits to prevent 'chunking' (i.e., combining single digits into larger numbers), or c) the switch condition (N = 46), in which the participants had to indicate whether or not each consonant rhymed with the Dutch word 'zee' (*sea*). There were four versions of each story, including consistent and inconsistent stories with far and close distances. We used a Latin square to construct four lists so each participant read only one version of each story. The order in which the stories were presented was randomized.

Participants read each story sentence-by-sentence on a computer screen, pressing the spacebar to advance to the next sentence. This allowed us to analyse reading times for each sentence separately. After each sentence a consonant was presented for 1000 ms. In the load condition, participants were instructed to keep these consonants in mind and report them back after the story. In the no-load condition, participants were instructed to ignore the consonants. In the switch condition participants were instructed to indicate whether or not each consonant rhymed with the Dutch word 'zee' (*sea*) by pressing '1' (yes) or '2' (no) on the number pad of the keyboard. Following each story participants answered a comprehension question about the content of the story with a 'yes' or 'no' button press (using the '1' and '2' keys on the number pad of the keyboard, respectively). In the load condition participants were then prompted to recall all 6 consonants in the presented order. Participants could type the consonants in an input box. Before continuing to the next story, a fixation cross was presented for 500 ms. After the reading task, participants completed an exit questionnaire consisting of questions to assess their motivation, use of strategies, and relative focus on comprehending the stories versus on recall of the consonants.

Procedure

Testing procedures were identical to those for Experiment 1.

Results

Comprehension questions and consonants recall

Before analysing the reading times, the responses to the comprehension questions, the number of correctly recalled consonants, and the accuracy on the rhyme-task were inspected. On average, participants answered 92% of the comprehension questions correctly in the no-load condition ($SD = 7\%$), and 84% correctly in the switch ($SD = 11\%$) and load condition ($SD = 10\%$). Furthermore, in the load condition participants correctly remembered on average 4.6 of the 6 consonants ($SD = 1.3$). In the switch condition, participants correctly indicated if the consonants rhymed or not for 3.7 of the 6 consonants ($SD = 2.2$). These findings indicate that participants were paying attention to the stories, the recall, and the rhyme task.

Table 5
The mean reading times and standard deviations in ms. as a function of condition (no-load, switch, load), consistency (consistent vs inconsistent), and distance (far vs close).

		Consistent		Inconsistent	
	Distance	*M*	*SD*	*M*	*SD*
No-load	Close	2228	1264	3037	1719
	Far	2365	1604	2722	1481
Switch	Close	2869	1547	3574	2130
	Far	2845	1721	3111	1638
Load	Close	4608	2780	4963	2664
	Far	4374	2555	5156	3076

Table 6
Wald tests of the model for the log-transformed reading times on the target sentences. The following R code was used: log(reading time) ~ 1 + condition * consistency * distance + (1 | subject) + (1 | item).

Wald test	χ2	Df	P
Condition	95.40	2	<.001*
Consistency	164.09	1	<.001*
Distance	16.11	1	<.001*
Condition*Consistency	15.333	2	<.001*
Condition*Distance	1.013	2	.603
Consistency*Distance	8.00	1	<.01*
Condition*Consistency*Distance	6.34	2	<.05*

Reading times

Extremely short or long reading times on the target sentence (shorter than 760 ms or longer than 14,911 ms, corresponding to the lowest 1% and highest 1%) were excluded from the analyses. Table 5 reports the means and standard deviations of the resulting reading times as a function of condition (no-load/switch/load), consistency (consistent/ inconsistent), and distance (far/close).

Table 6 reports the results of the Wald tests of the random-intercepts-only LMEM for the log-transformed reading times on the target sentence. The results revealed significant main effects for condition, consistency, and distance, as well as condition by consistency, consistency by distance, and condition by distance by consistency interaction effects. Inspection of the estimates of the main effects showed that reading times of the target sentence were significantly longer in the load condition than in the no-load ($\widehat{\beta} = 0.59$, SE = 0.061, df = 158, $t = 9.63$, $p < .0001$) and switch condition ($\widehat{\beta} = 0.41$, SE = 0.066, df = 158, $t = 6.21$, $p < .0001$). The reading times in the switch condition were also significantly longer than in the no-load condition ($\widehat{\beta} = -0.18$, SE = 0.064, df = 158, $t = -2.83$, $p < .05$). For inconsistent targets the reading times were longer than for consistent targets ($\widehat{\beta} = -0.16$, SE = 0.013, df = 4183, $t = -12.6$, $p < .0001$) and reading times were longer when the distance was close rather than far ($\widehat{\beta} = 0.055$, SE = 0.013, df = 4184, $t = 4.20$, $p < .0001$).

Follow-up analyses of the significant condition by consistency interaction revealed an inconsistency effect for the no-load condition ($\widehat{\beta} = -0.22$, SE = 0.021, df = 4183, $t = -10.6$, $p < .0001$), the switch condition ($\widehat{\beta} = -0.17$, SE = 0.024, df = 4180, $t = -6.96$, $p < .0001$), and the load condition ($\widehat{\beta} = -0.10$, SE = 0.023, df = 4180, $t = -4.53$, $p < .0001$). The condition by consistency interaction emerged because the inconsistency in the no-load condition was significantly larger than in the load condition ($\widehat{\beta} = 0.12$, SE = 0.031, df = 4181, $t = 3.91$, $p < .0001$). The two remaining contrast analyses fell just short of significance (no-load vs. switch: $\widehat{\beta} = -0.057$, SE = 0.032, df = 4179, $t = -1.79$, $p = .074$; load vs. switch: $\widehat{\beta} = 0.064$, SE = 0.029, df = 4180, $t = 1.94$, $p = .052$). Together these results suggest that the following order is present concerning the size of the inconsistency effect: no-load > switch > load.

Table 7
Results of the inconsistency contrasts for all possible distance and condition combinations.

Condition	Distance	$\hat{\beta}$	SE	df	T	P
No-load	Close	−0.28	0.030	4183	−9.53	<.0001*
	Far	−0.16	0.029	4179	−5.47	<.0001*
Switch	Close	−0.22	0.034	4184	−6.50	<.0001*
	Far	−0.11	0.033	4171	−3.34	<.001*
Load	Close	−0.092	0.031	4180	−2.92	<.01*
	Far	−0.11	0.032	4177	−3.49	<.001*

Follow-up analyses of the significant consistency by distance interaction revealed an inconsistency effect for the close distance ($\hat{\beta} = -0.20$, SE = 0.018, df = 4184, $t = -10.8$, $p < .0001$) and the far distance ($\hat{\beta} = -0.13$, SE = 0.018, df = 4177, $t = -7.01$, $p < .0001$). The consistency by distance interaction emerged because the inconsistency effect was significantly larger in the close distance than in the far distance ($\hat{\beta} = -0.071$, SE = 0.026, df = 4179, $t = -2.76$, $p < .01$).

The follow-up analyses of the three-way interaction in the simple model revealed a significant inconsistency effect for all condition by distance combinations (see Table 7 and Fig. 2). Further analyses showed that for the close distance the inconsistency effect was weaker in the load condition than in the other two conditions (load vs. no-load: $\hat{\beta} = 0.19$, SE = 0.043, df = 4182, $t = 4.41$, $p < .0001$; load vs. switch: $\hat{\beta} = 0.13$, SE = 0.047, df = 4182, $t = 2.77$, $p < .01$), whereas the size of the inconsistency effect did not differ significantly between the no-load and switch conditions ($\hat{\beta} = -0.063$, SE = 0.045, df = 4182, $t = -1.39$, $p = .16$). In the far distance condition the size of the inconsistency effect did not differ significantly between the no-load, switch, and load conditions (no-load vs. switch: $\hat{\beta} = -0.050$, SE = 0.044, df = 4173, $t = -1.13$, $p = .26$; no-load vs. load: $\hat{\beta} = 0.049$, SE = 0.044, df = 4177, $t = 1.11$, $p = .26$; switch vs. load: $\hat{\beta} = -0.0015$, SE = 0.046, df = 4174, $t = -0.032$, $p = .97$). Furthermore, when comparing the inconsistency effect between close and far distance, the size of the inconsistency effect increased at the close distance relative to the far distance for both the no-load condition ($\hat{\beta} = 0.12$, SE = 0.042, df = 4179, $t = 2.96$, $p < .01$) and the switch condition ($\hat{\beta} = 0.11$, SE = 0.048, df = 4176, $t = 2.33$, $p < .05$), yet remains constant in the load condition ($\hat{\beta} = -0.020$, SE = 0.045, df = 4177, $t = -0.44$, $p = .66$).

The results of the maximal LMEM confirmed the main effects and interaction effects observed in the simple model analyses, except that the three-way condition by distance by consistency interaction did not reach significance. Nevertheless, follow-up analyses parallel to those of the simple model confirmed the effects of the simple model (see Appendix C).

Discussion Experiment 2

The main aim of Experiment 2 was to elucidate whether availability of information plays a role in the effect of working memory load on coherence monitoring. To manipulate the availability of information we varied the distance between the context sentences and the target sentences. The results showed a stronger inconsistency effect when information was more available (i.e., in the close distance condition), but only in the switch and no-load conditions. In contrast, in the load condition the strength of the inconsistency effect did not increase significantly when the conflicting information was made more available by decreasing textual distance. The results suggest that working memory load interferes with the integration/validation of incoming information regardless of the availability of the conflicting context information. The secondary aim of Experiment 2 was to control for the possibility that the continuous task-switching in the load condition interfered with building a coherent mental representation because of repeated redirecting of the focus of attention (i.e., executive control), rather than filling up the capacity of the focus of attention itself. To disentangle the respective influences of working memory capacity and executive control on coherence monitoring we added a switching condition, which puts strain on executive control, but not necessarily on the capacity of the focus of attention. For the close distance, there was a significant difference between conditions in the size of the inconsistency effect, with the load condition showing a reduced inconsistency effect relative to both the switch condition and the no-load condition. The size of the inconsistency effect did not differ significantly between the no-load and switch conditions. These findings suggest that the reduced inconsistency effects in the load condition are predominantly caused by working memory capacity constraints and not by task-switching demands. It is worth noting that we did not observe significant differences in the strength of the inconsistency effect between conditions for the far distance. This null-effect is at odds with the finding in Experiment 1 where, in a similar 'far' situation, a significant difference in inconsistency effect between load and no-load conditions was observed. This difference may be caused by the between-subject design of Experiment 2 compared to the within-subject design of Experiment 1, which may have resulted in reduced power in Experiment 2. Another discrepancy between findings of the two experiments is the significant inconsistency effect in the load condition of Experiment 2. We can only speculate about potential explanations for this effect, but one possibility is that participants in Experiment 2 completed fewer trials and, thus, may have experienced less fatigue. Importantly, however, both Experiment 1 and Experiment 2

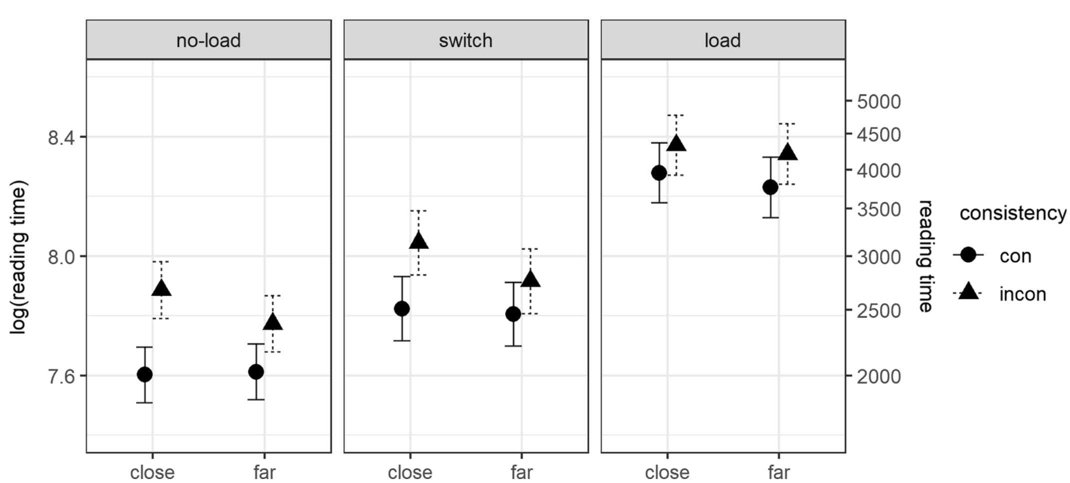

Fig. 2. Mean reading times on consistent and inconsistent target sentences in the no-load, switch, and load conditions for close and far distance.

showed a significant condition by consistency interaction, illustrating that the inconsistency effect is significantly *reduced* by an external working memory load.

General discussion

The aim of the current study was to elucidate the role of working memory capacity in reading comprehension, in particular in the online processes involved in coherence monitoring. To investigate online coherence monitoring we used the contradiction paradigm (O'Brien & Albrecht, 1992) and added a secondary task to put a load on working memory capacity. The results show that the addition of an external working memory load interfered with coherence monitoring, as reflected in a reduced response to inconsistencies (Experiments 1 and 2). In addition, we investigated whether the effect of working memory load on coherence monitoring is moderated by the availability of information, by manipulating the distance between the inconsistent sentences. The results show that the degree of availability of the conflicting context information indeed influenced coherence monitoring, with greater availability (i.e., close distance) leading to a stronger inconsistency effect (Experiment 2). Importantly, however, this effect of availability was only present when there was no load on working memory capacity. When there was a load, making the conflicting context information more available did not significantly increase inconsistency detection. Thus, load reduces the inconsistency effect regardless of availability.

The role of working memory capacity in coherence monitoring

We investigated the potential role of working memory capacity in coherence monitoring because coherence monitoring is a crucial component of successful reading comprehension and because it is a process that proficient readers execute continually and routinely as they proceed through a text. We considered two possibilities, a) that coherence monitoring is an effortless and relatively automatic process that does not draw on working memory resources and b) that it is an effortful process that requires relevant information to be held and processed within working memory capacity.

The results in both experiments show an inconsistency effect in the no-load condition but a reduced inconsistency effect in the load-condition, indicating that coherence monitoring requires working memory capacity. In addition, the results of Experiment 2 show that variation in the availability of the conflicting context information affected inconsistency detection, but only when there was no load. When an external working memory load was present, no significant difference was observed between the far and close distance. Thus, the detrimental effect of working memory load on coherence monitoring is not moderated by the degree of availability of conflicting information.

These findings indicate that working memory capacity influences coherence monitoring and, more specifically, is required for the integration and validation processes that are part of inconsistency detection. Thus, whereas passive, spread-of-activation processes may lead to activation of the relevant information (Kintsch, 1988; Myers & O'Brien, 1998; Van den Broek et al., 1999) the comparison of the activated information likely draws on working memory resources. As an aside, the findings also call into question the assumption that increasing textual distance simply increases working memory load (see also Currie et al., 2020; Oakhill, Hartt, & Samols, 2005; Yuill, Oakhill, & Parkin, 1989).

The interplay between memory and reading comprehension

The findings of the current study can be interpreted in the context of the memory framework described in the Introduction. This framework, which is based on the embedded-processes model (Cowan, 1988, 1999, 2001; Adams, Nguyen, & Cowan, 2018) and the long-term working memory framework (Ericsson & Kintsch, 1995), focuses on the interaction between working memory and long-term memory. According to the framework, working memory consists of a short-term, limited capacity system that is available under all conditions and activated portions of long-term memory that in principle can be unlimited but are only available for well-established knowledge domains. Application of this framework to the current results and to reading models in general raises several key points.

One key point is that during comprehension and knowledge-construction activities such as reading, portions of long-term memory may be activated relative to their resting states. These activated portions would include background knowledge that is semantically associated with the current contents of working memory capacity as well as the memory representation of the text as it has been read so far. The content of these activated portions have privileged status in that, although they are not in the focus of attention, they are 'pre-potent' and can be easily accessed. Such access may occur relatively automatically, for example through spread of activation (Kintsch, 1988; Cook & O'Brien, 2014), but the current results show that coherence monitoring is not automatic, as it requires working memory capacity. Interestingly, the results on the comprehension questions of our study suggest automatic processing of information of a different kind. Even in the load conditions, participants answered more than 80% of the comprehension questions correctly. Apparently, despite the load and the resulting incomplete inconsistency detection, information from the texts found their way into the memory representations of those texts. These findings are consistent with and extend classical work by Baddeley and Hitch (1974), whose dual-task studies showed that basic text comprehension is largely unaffected when subjects are asked to remember a series of digits during reading. Thus, readers can handle multiple tasks that decrease the availability of working memory capacity with only minor performance decrements with respect to basic memory representation. Such findings also are consistent with the notion that the mental representation of the text does not reside working memory capacity but rather in the activated portion of long-term memory, where it has privileged status of easy accessibility.

A second key point is that, although information relevant for comprehension is readily available in the activated portions of long-term memory, processes that *use* this information consume working memory resources. Whereas this is to be expected for processes that are clearly involved and intentional (e.g. reflection, evaluation) our results show that this also applies to more routinized and basic comprehension processes such as the integration and validation component of coherence monitoring. An interesting direction for future research would be to examine other components of reading comprehension and determine which reading processes can occur relatively automatically and which require working memory capacity.

A third key point is that the activated portions of long-term memory change as the reader progresses from sentence to sentence. With each sentence the content of the focus of attention shifts, triggering a new passive spread of activation through the reader's background knowledge and the evolving mental representation of the text. Moreover, each sentence may also trigger reader-initiated processes that further activate portions of long-term memory. The idea of a fluctuating pattern of activation in long-term memory as the reader progresses through a text is captured in the Landscape model of reading comprehension (e.g., Van den Broek et al., 1999). In this model, the 'landscape of activations' changes with each reading cycle. New concepts will be temporarily activated, some currently activated ones will be kept active and others deactivated, depending on the information in the text and the knowledge structures (node strengths) in long-term memory. In the context of the current studies, the more pronounced inconsistency effect during normal reading in the close than in the far distance condition is consistent with this notion of a fluctuating availability. The finding that this effect disappears in the load condition raises the interesting question whether the working memory load interferes with the integration of information or already interferes at an earlier stage by preventing the passive, spread-of-activation processes. To answer this question, it may be useful to expand the dimensions of availability under consideration beyond the one used in the current study, namely distance. For instance, the degree of elaboration of the target information in long-term memory or the cue-target overlap (Sanford & Garrod, 1981), the type of associative connection between cue-target (e.g., causality - Kendeou & O'Brien, 2014) may influence availability that differ from those triggered by distance.

Extending the framework to other complex knowledge domains

The current findings, as well as theories of long-term working memory, the embedded-processes model, and the Landscape model (Ericsson & Kintsch, 1995; Cowan, 1988, 1999, 2001; Adams, Nguyen, & Cowan, 2018; Van den Broek et al., 1999), highlight the distinction between a very limited workspace for storage and processing and a larger, fluctuating landscape of activated portions of long-term memory that influences the availability of information. Together they give us a better understanding of how different memory systems collaborate during reading and how each memory system influences different aspects of meaning construction. Although this is described in the context of reading comprehension, we propose that it applies to many other complex activities that involve knowledge construction as well. In daily life, at work, and in school, similar processes take place: meaning construction based on large amounts of information, both from the situation at hand and from one's background knowledge. Such activities range from mathematics, problem solving, playing chess, to everyday (but complex) tasks such as following a recipe. For example, imagine a graduate student who is trying to solve a physics problem about the force needed to pull a cart up an incline; the student needs to keep track of multiple pieces of information (mass of the cart, slope, gravitational force, and so on) and computationally integrate these pieces of information as they solve the problem. In addition, portions of the student's long-term memory are activated from relevant knowledge structures (e.g., about gravity, applicable laws of physics), and may be used to temporarily store parts of the problem and solution, freeing up working memory capacity for the integration of information, and detection of inconsistent or conflicting pieces of evidence. Similar to reading, such problem solving is dynamic and each step of the solution process requires different pieces of information to be processed and activated. Here too, this results in a fluctuating landscape of activations in long-term memory. Similar processes take place during more everyday activities. For example, during cooking, a recipe will activate relevant knowledge structures in long-term memory (e.g., knowledge about different ingredients, cooking procedures, culinary preferences of the intended guests), whereas the limited capacity workspace is primarily used for processing and integrating currently salient information, storage of retrieval cues, and coherence monitoring processes relevant to the domain of cooking (e.g. monitoring the order of recipe steps, intermediate outcomes, and parallel processes such as cooking the pasta and cutting the vegetables). Again, this process is dynamic as each step of the recipe requires different pieces of information to be activated. In each case, the framework makes clear why success is most likely for experienced readers, problem solvers, or cooks; if one does not know what 'bain-marie' or 'Julienne cut' means, more information will have to be kept active in workspace and less information can be relegated to activated portions of long-term memory, causing interference with the processing demands of the task at hand (and the quality of the resulting meal).

Conclusion

Reading comprehension and other complex real-life tasks have in common that they involve meaningful content, and rely on existing knowledge structures. They also have in common that they revolve around meaning construction and the combination of different pieces of information into a meaningful whole. For example, processing a text is substantially different from processing isolated pieces of information. This poses a challenge for research on the role of working memory in reading comprehension, as most standard working memory tasks use isolated objects of pieces of information (e.g., Corsi Block, Digit Span), and may explain why many studies fail to find a strong correlation between performance on working memory tasks and measures of reading comprehension. Our findings illustrate that working memory capacity, in fact, does play an important role in integration and validation processes required to monitor and maintain coherence and when dealing with contradicting or confusing information. Paradigms such as the one used in the current studies can be extended to other complex knowledge domains, capitalizing on the need for fine-grained models of working memory that specify which components of complex cognitive tasks are more and which are less dependent on a limited capacity working memory system.

Open Science Framework view-only-link to data, stimuli, and code: https://osf.io/r25t6/?view_only=fe1b27dce66847428dd0f3d46464107d.

Link to online dashboard to explore data and analyses: https://mtbfan.shinyapps.io/LMEMSpaperAB/.

CRediT authorship contribution statement

Amy de Bruïne: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Dietsje Jolles:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing. **Paul van den Broek:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing.

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Appendix A. Overview of all stories

Story number	Context sentences (consistent = C and inconsistent = I)	Target sentence
1*	A lot of Sem's family members also enjoy watching the stars (C) Nobody in Sem's family enjoys watching the stars (I)	Sem's brother is an astronomer so they watch the stars together.
2	Lucas wants to throw a pool party (C) Lucas wants to throw a disco party (I)	Sophie can't come because she can't swim.
3	Milan thinks his dad's job is very cool (C) Milan thinks is dad's job is very lame (I)	Milan is very excited to join his dad during work for a day.
4*	Daan lives on a quiet street near a big forest (C) Daan lives in a busy street in the middle of a big city (I)	*(additional context: Daan and his friends play hide and seek)* After hours of searching they find her in the forest.
5*	Tim's uncle once gave him a book about airplanes (C) Tim's uncle once took him on a trip his own plane (I)	Tim states his fascination with airplanes began when his uncle gave him a book about airplanes.
6*	Levi is sad to leave his school and never see his classmates again (C) Levi is happy to leave his school and never see his annoying classmates again (I)	Levi often thinks back to all the good memories of his old school.
7*	Emma joins her school's reading competition for the first time (C) Last year Emma won her school's reading competition (I)	Emma is very nervous for the competition as it is her first time competing.
8*	Lotte's parents are very religious and strict (C) Lotte's parents are not religious or strict (I)	Lotte's parents do not allow this as it goes against their religion.
9*	The wheels of Thomas' toy car broke off (C) The doors of Thomas' toy car broke off (I)	In the shop they repair the wheels of the toy car.
10	Thijs does not like languages and thinks learning English is useless (C) Thijs likes languages and thinks learning English is very useful (I)	Thijs does not pay attention during his English class, because it's his least favorite class.
11*	Jesse is always very loud and disturbs a lot of classes (C) Jesse is always very quiet and never disturbs classes (I)	The teacher is fed up with Jesse and expels him from the class.
12*	Luuk started karate after he saw a movie about it (C) Luuk started karate after he saw his sister compete (I)	Unfortunately, Luuk's sister does not like karate.
13	Eva thinks being a model is difficult and requires a lot of practice (C) Eva thinks being a model is easy and only requires beauty (I)	Eva practices very hard for her modelling competition.
14*	Stijn got a drum kit for his birthday (C) Stijn got a guitar for his birthday (I)	His neighbors are annoyed by the noise of his drum kit.
15	Lisa designs and makes her own clothes (C) Lisa creates and cooks her own meals (I)	Lisa's fashion show was a great success.
16*	Ruben borrows all his books at the library (C) Ruben buys all his books at the book shop (I)	Ruben decides he is not returning the book to the library.
17*	Lieke would like a bike for her birthday (C) Lieke would like a stuffed animal for her birthday (I)	Today they are picking up her present at the bike shop.
18	Lars and his brothers attend the same school (C) Lars and his brothers attend different schools (I)	Lars and his brothers are on the school's football team.
19	Together Sanne en Noa are always very loud (C) Together Sanne and Noa are always very quiet (I)	The teacher separates Sanne and Noa because they are disturbing the class.
20	It's summer and Finn is bored because he broke his leg (C) It's winter and Finn is bored because he broke his leg (I)	Bram is going swimming in the lake, but Finn can't come.
21*	Julian is going to Paris with his mom (C) Julian is going to Paris with his brother (I)	Julian's brother is jealous because he can't come.
22	The house is very clean, because Anna's mom values tidiness (C) The house is messy, but Anna's mom doesn't mind (I)	After the party, Anna's mom is annoyed with the mess.
23	Mees' grandparents live in a big city (C) Mees' grandparents live in a small village (I)	To get to his grandparents Mees needs to ride the subway.
24	Isa's parents don't allow Isa to spend too much time on the computer (C) Isa's parents are proud Isa is very skilled with the computer (I)	When Isa's parents get home, they are upset to find her on the computer.
25	*(Additional context: Sven's bike is stolen)* Sven goes to the police station immediately (C) The police station is already closed (I)	The cop asks Sven if he put a lock on his bike.
26	Fleur got her cat from a shelter (C) Fleur got her cat from a friend (I)	If Fleur doesn't take care of her cat, her mom will return the cat to the shelter.
27*	Lynn and Tess will sing a song for the talent show (C) Lynn and Tess will do a dance for the talent show (I)	Tess broke her toe so they can't compete in the talent show.
28	Yesterday, Max hit his head while playing outside (C) Yesterday, Max became sick during lunch (I)	Next time Max will more attention when he plays outside.
29	Gijs is a talented singer (C) Gijs is a talented tennis player (I)	One of the jurors is his favorite singer.
30	Sara got her exam results back and she failed math (C) Sara got her exam results back but she lost them (I)	Sara's parents are not upset and hire a tutor to help with math.
31	The weather forecast is bad with snow and a lot of wind (C) The weather forecast is good with a clear sky and a lot of sun (I)	Liam is happy with his warm cap.
32	Roos and Maud are nervous because they have never travelled by train before (C) Roos and Maud are relaxed because they often travel by train.	Roos and Maud's stomachs ache because they are so nervous.
33*	Femke's mom asked her to buy a cake (C) Femke's mom asked her to buy some bread (I)	Once Femke is back home they enjoy the delicious cake.
34*	Teun's school is organizing a sponsored run to collect money (C) Teun's school is organizing a garage sale to collect money (I)	Teun is training extra hard to run as much laps as possible.
35*	Zoë wants to surprise her mom with pretty flowers (C) Zoë wants to surprise her mom with pretty earrings (I)	When they get home Zoë puts the flowers in a vase.
36*	Nick's favorite instrument is the trumpet (C) Nick's favorite instrument is the piano (I)	It is Nick's dream to become a famous for playing his trumpet.
37*		Anouk's grandma is not yet allowed to walk with her new knee.

(*continued on next page*)

(*continued*)

Story number	Context sentences (consistent = C and inconsistent = I)	Target sentence
	Anouk's grandma needs a knee surgery (C) Anouk's grandma needs a wrist surgery (I)	
38*	Iris orders a large strawberry sorbet (C) Iris orders a large chocolate sorbet (I)	Iris notices the big pink stain on her shirt.
39	Jan and Stan like to build tree houses in the forest (C) Jan and Stan like to play videogames (I)	Even when it is raining Jan and Stan are playing in the forest.
40*	Naomi and her friend are going to the zoo (C) Naomi and her friend are going to a theme park (I)	Naomi always enjoys a trip to the zoo.
41	Daniël decided to order food from the Burger King (C) Daniël decided to order food from Domino's (I)	Everybody at the party ordered a burger.
42*	Floris' mom always picks him up after school (C) Floris' nanny always picks him up after school (I)	When the school bell rings, Floris' mom is already waiting outside.
43	Britt plays the piano and has a lesson tonight (C) Britt plays the flute and has a lesson tonight (I)	Britt hopes her piano teacher doesn't notice her mistakes.
44*	Luna likes all the ice cream flavors, but banana is her favorite (C) Luna likes ice cream, expect banana flavored ice cream (I)	Luna orders a big banana sorbet with extra whipped cream.
45	It is freezing, so Ryan quickly turns on the heater (C) It is very hot, so Ryan quickly turns on the air conditioning (I)	Ryan puts on his warmest jacket and goes outside.
46	Tom really likes reading and does well in school (C) Tom really dislikes ready, but is doing well in school (I)	Tom's mom wants to buy him some books and Tom is very excited as he likes reading a lot.
47	Koen has a swimming certificate, so he is a good swimmer (C) Koen does not have a swimming certificate and can't swim (I)	Koen dives off the boat to swim in the water.
48*	Amber loves all animals and cats are her favorite (C) Amber loves all animals, but is allergic to cats (I)	Amber and her mom pick up the kitten.
49*	Tygo eats almost everything, expect fish (C) Tygo eats almost everything, expect chicken (I)	Tygo orders some chicken nuggets.
50	Mila's mom just had a healthy baby boy (C) Mila's mom just had a healthy baby girl (I)	At school, Mila tells everyone about her new baby brother.
51	Today is the first day of the summer break (C) Today is the first day of the Christmas break	Nikki is happy that is finally summer.
52*	Joep's arm is hurting bad (C) Joep's leg is hurting bad (I)	All of Joep's friends write something on the cast on his arm.
53	In the pet shop Laura picks a little puppy (C) In the pet shop Laura picks a little kitten (I)	Laura grabs a ball and plays in the garden with her new puppy.
54	Maria is very excited to give a presentation and she can't wait to tell everyone about her topic (C) Maria is very nervous to give a presentation and wants to postpone it as long as possible (I)	Maria volunteers to go first on the presentation day.
55*	Vera's baby sister is still too young to play with Vera (C) Vera has no siblings to play with (I)	Vera's dad and baby sister come to watch Vera's tree house.
56	Cas likes the winter, especially when it is snowing (C) Cas dlislikes the winter, especially when it is snowing (I)	Cas favorite sport is skiing.
57*	Demi's room is usually a mess and she is always searching for her stuff (C) Demi's room is usually very clean and she never loses her stuff (I)	Demi can't find her essay because her room is so messy.
58	Bo's dad is moving to Germany (C) Bo's dad is moving to France (I)	On the day of his dad departure to Germany, Bo is a little sad/.
59*	Marit lives in a house with a large garden (C) Marit lives on the 6th floor and doesn't have a garden (I)	They enjoy the cookies in the garden.
60	Luckily, a lot of dishes fit in the dish washer (C) Unfortunately, they don't have a dish washer (I)	After dinner, Elise fills the dish washer with dirty plates.
61*	Yara and her dad bought a big can of red paint (C) Yara and her dad bought a big can of yellow paint (I)	The wall in Yara's room are just as red as she had hoped.
62	Willem just turned 20 and is training for a marathon (C) Willem just turned 80 and recently got a cane (I)	Willem runs to the boy and picks him up.
63*	Bas currently has no guitar lessons, because his teacher is sick (C) Bas currently has no guitar lessons, because he broke his wrist (I)	Bas is practicing on his guitar for the performance.
64*	Ilse is fluent in English and understands it well (C) Ilse doesn't speak English and has trouble understanding it (I)	Ilse and Liv become friends and chat in English all day.

* An asterisk indicates the stories that were used in Experiment 2.

Appendix B. Results of the maximal random effect structure models of Experiment 1

The results of the Wald tests revealed significant main effects for the factors condition and consistency, and a significant condition by consistency interaction (see Table A1). The reading times in the load condition were longer than the reading times in the no-load condition ($\widehat{\beta} = 0.67$, SE = 0.060, df = 43.3, $t = 11.03$, $p < .0001$). Furthermore, reading times were longer for inconsistent targets than for consistent targets ($\widehat{\beta} = -0.090$, SE = 0.019, df = 38, $t = -4.69$, $p < .0001$).

Follow-up analyses of the significant condition by consistency interaction revealed that the inconsistency effect was larger in the no-load condition than in the load condition ($\widehat{\beta} = 0.11$, SE = 0.037, df = 33.3, $t = 3.03$, $p < .01$). More specifically, the inconsistency effect was significant in the no-load condition ($\widehat{\beta} = -0.15$, SE = 0.026, df = 34.7, $t = -5.65$, $p < .0001$) but not significant in the load condition ($\widehat{\beta} = -0.034$, SE = 0.027, df = 38.6, $t = -1.23$, $p = .23$).

Table A1
Wald tests of the model for the log-transformed reading times on the target sentences. The following R code was used: log(reading time) ~ 1 + condition * consistency + (1 + condition * consistency| subject) + (1 + condition * consistency| item).

Wald test	χ2	Df	P
Condition	139.93	1	<0.001*
Consistency	23.88	1	<0.001*
Condition*Consistency	9.18	1	<0.01*

Appendix C. Results of the maximal random effect structure models of Experiment 2

The results of the Wald tests revealed significant main effects for condition, consistency, and distance, as well as condition by consistency and consistency by distance interaction effects (see Table B1).

Inspection of the estimates of the main effects showed that reading times of the target sentence were significantly longer in the load condition than in the no-load ($\widehat{\beta} = 0.59$, SE = 0.067, $z = 8.79$, $p < .0001$) and switch condition ($\widehat{\beta} = 0.41$, SE = 0.066, $z = 5.91$, $p < .0001$). The reading times in the switch condition were also significantly longer than in the no-load condition ($\widehat{\beta} = -0.18$, SE = 0.056, $z = -3.27$, $p < .01$). For inconsistent targets the reading times were longer than for consistent targets ($\widehat{\beta} = -0.16$, SE = 0.018, $z = -8.97$, $p < .0001$) and reading times were longer when the distance was close rather than far ($\widehat{\beta} = 0.06$, SE = 0.016, $z = 3.35$, $p < .001$).

Follow-up analyses of the significant condition by consistency interaction revealed an inconsistency effect for the no-load condition ($\widehat{\beta} = -0.22$, SE = 0.028, $z = -7.85$, $p < .0001$), the switch condition ($\widehat{\beta} = -0.16$, SE = 0.027, $z = -6.04$, $p < .0001$), and the load condition ($\widehat{\beta} = -0.10$, SE = 0.031, $z = -3.26$, $p < .01$). The condition by consistency interaction emerged because the inconsistency in the no-load condition was significantly larger than in the load condition ($\widehat{\beta} = 0.12$, SE = 0.04, $z = 3.01$, $p < .01$). The two remaining contrast analyses were not significant (no-load vs. switch: $\widehat{\beta} = -0.059$, SE = 0.037, $z = -1.60$, $p = .109$; load vs. switch: $\widehat{\beta} = 0.063$, SE = 0.039, $z = 1.61$, $p = .107$). In all, together these results do suggest that the following order is present concerning the size of the inconsistency effect: no-load > switch > load.

Follow-up analyses of the significant consistency by distance interaction revealed an inconsistency effect for the close distance ($\widehat{\beta} = -0.20$, SE = 0.024, $z = -8.21$, $p < .0001$) and the far distance ($\widehat{\beta} = -0.13$, SE = 0.024, $z = -5.20$, $p < .0001$). The consistency by distance interaction emerged because the inconsistency effect was significantly larger in the close distance ($\widehat{\beta} = -0.071$, SE = 0.032, $z = -2.20$, $p < .05$).

Even though the results of the three-way condition by distance by consistency interaction were not confirmed by the results of the maximal LMEM ($\chi2 = 3.74$, df = 2, $p = .15$), we did include the follow-up analyses parallel to ones of the simple model. These analyses revealed a significant inconsistency effect for all condition by distance combinations (see Table C1). Further analyses showed that in the close distance condition the inconsistency effect was weaker in the load condition than in the other conditions (load vs. no-load: $\widehat{\beta} = 0.19$, SE = 0.051, $z = 3.75$, $p < .001$; load vs. switch: $\widehat{\beta} = 0.13$, SE = 0.053, $z = 2.36$, $p < .05$), yet the size of the inconsistency effect did not differ significantly between the no-load and switch conditions ($\widehat{\beta} = -0.063$, SE = 0.051, $z = -1.28$, $p = .20$). In the far distance condition the size of the inconsistency effect did not differ between the no-load, switch, and load conditions (no-load vs. switch: $\widehat{\beta} = -0.050$, SE = 0.051, $z = -1.01$, $p = .31$; no-load vs. load: $\widehat{\beta} = 0.049$, SE = 0.060, $z = 0.87$, $p = .39$; switch vs. load: $\widehat{\beta} = -0.0015$, SE = 0.059, $z = -0.001$, $p = 1.00$). A somewhat different, yet equally valid interpretation of the three-way

Table B1
Wald tests of the model for the log-transformed reading times on the target sentences. The following R code was used: log(reading time) ~ 1 + condition * consistency * distance + (1 + condition * consistency * distance | subject) + (1 + condition * consistency * distance | item).

Wald test	χ2	Df	P
Condition	79.92	2	<.001*
Consistency	80.21	1	<.001*
Distance	8.68	1	<.01*
Condition*Consistency	11.18	2	<.01*
Condition*Distance	1	2	.608
Consistency*Distance	7.25	1	<.01*
Condition*Consistency*Distance	3.74	2	.15

Table C1
Results of the inconsistency contrasts for all possible distance and condition combinations.

Condition	Distance	$\widehat{\beta}$	SE	z	p
No-load	Close	−0.28	0.039	−7.21	<.0001*
	Far	−0.16	0.035	−4.65	<.0001*
Switch	Close	−0.22	0.037	−5.92	<.0001*
	Far	−0.11	0.039	−2.80	<.01*
Load	Close	−0.091	0.039	−2.32	<.05*
	Far	−0.11	0.048	−2.30	<.05*

interaction is that relative to the close distance condition, the size of the inconsistency effect diminishes in the far distance condition for the no-load ($\widehat{\beta} = -0.12$, SE $= 0.048$, $z = -2.56$, $p < .05$) and switch condition ($\widehat{\beta} = -0.11$, SE $= 0.053$, $z = -2.04$, $p < .05$), yet remains constant in the load condition ($\widehat{\beta} = 0.018$, SE $= 0.062$, $z = 0.30$, $p = .77$).

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