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Temporal–contextual processing in working memory: Evidence from delayed cued recall and delayed free recall tests

Vanessa M. Loaiza · David P. McCabe

Abstract Three experiments are reported that addressed the nature of processing in working memory by investigating patterns of delayed cued recall and free recall of items initially studied during complex and simple span tasks. In Experiment 1, items initially studied during a complex span task (i.e., operation span) were more likely to be recalled after a delay in response to temporal–contextual cues, relative to items from subspan and supraspan list lengths in a simple span task (i.e., word span). In Experiment 2, items initially studied during operation span were more likely to be recalled from neighboring serial positions during delayed free recall than were items studied during word span trials. Experiment 3 demonstrated that the number of attentional refreshing opportunities strongly predicts episodic memory performance, regardless of whether the information is presented in a spaced or massed format in a modified operation span task. The results indicate that the content–context bindings created during complex span trials reflect attentional refreshing opportunities that are used to maintain items in working memory.

Keywords Working memory · Episodic memory · Span tasks · Serial position effects

Understanding the underlying processes that support immediate memory has considerable implications for the fundamental questions of how once-transient information becomes accessible over the long term. Research investigating working memory (WM) has focused on the particular mechanisms that support the maintenance of different representations and task goals (Barrouillet, Bernardin, & Camos, 2004; Cowan, 1999; McCabe, 2008; Oberauer, 2002). One method of understanding encoding processes in WM is to examine long-term episodic memory for information originally studied in different types of WM tasks. Specifically, in the present study, we employed a comparison of simple and complex span tasks to investigate the long-term consequences of encoding processes in WM. Complex span tasks test WM capacity by requiring participants to maintain and manipulate information effectively (Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005; Engle, 2002). For example, the operation span task (Turner & Engle, 1989) requires participants to solve an arithmetic problem (e.g., 7 × 4 = 28?) and then to maintain a word that is presented after the problem. This problem–word sequence is typically repeated two to six times per trial, until a cue is given to recall all words from that trial. Thus, operation span assesses WM capacity by requiring a cognitively demanding processing component (i.e., the arithmetic problem) along with temporary maintenance of information (i.e., recall of the words). Conversely, simple span tasks likely require only brief storage of information. In the word span task, for example, between two and eight successive words are presented, followed by a cue to recall the words. Unsworth and Engle (2006, 2007) showed that longer list lengths in a simple span load onto a separable factor and more strongly predict fluid intelligence than do short list lengths in a simple span, and thus may tax WM capacity in a way similar to complex span tasks. However, the specific types of processing engaged during WM encoding remain unclear. As such, we sought to examine the encoding processes engaged by tasks purported to measure WM capacity, by examining potential differences in episodic memory performance between items initially processed during simple and complex span tasks.

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A variety of recent studies have indicated that information in WM is maintained by retrieving previously active information back into the focus of attention (Barrouillet et al., 2004; Camos, Lagner, & Barrouillet, 2009; McCabe, 2008; Unsworth & Engle, 2008). The information must be retrieved because other task goals (e.g., completing an arithmetic problem during operation span) can disrupt its maintenance. This mechanism of retrieval is often referred to as *focus switching* (Unsworth & Engle, 2008; Verhaeghen & Hoyer, 2007), *refreshing* (Higgins & Johnson, 2009; Johnson, Reeder, Raye, & Mitchell, 2002), or *attentional refreshing* (Barrouillet et al., 2004; Camos et al. 2009; Hudjetz & Oberauer, 2007). For the purposes of clarity, we will henceforth refer to this mechanism as "attentional refreshing." Attentional refreshing is considered to be a domain-general mechanism of maintenance that operates by retrieving previously presented information during pauses between completing the processing component of a task and presentation of the to-be-remembered items (Barrouillet et al., 2004; Camos et al., 2009; Camos, Mora, & Oberauer, 2011; Hudjetz & Oberauer, 2007; McCabe, 2008). Thus, previously presented information that is no longer active is retrieved through attentional refreshing.

In addition to attentional refreshing, binding representations to source contexts may also be important for WM performance. Specifically, Oberauer and colleagues' *concentric model* (Oberauer, 2002, 2005, 2009; Oberauer et al. 2007) proposed that WM supports complex cognition by allowing representations in WM (e.g., words or events) to be bound to specific contexts (e.g., temporal position within a list). These bindings are dynamic, in that they can be updated or dissolved depending on the demands of the task (Oberauer, 2009; Oberauer & Vockenberg, 2009). Oberauer et al. (2007) also suggested that a source context may be temporal in nature, such that the original order of the presented information can be used as the context to which information is bound.

McCabe (2008) demonstrated that the durability of a content–context binding may be related to the opportunity to attentionally refresh the previously presented representation. For example, McCabe administered a simple span task and a complex span task, each with trial lengths between two and four words to remember, followed by a delayed recall test. The results showed that delayed recall performance was greater for items presented during a complex rather than a simple span task. In McCabe's *covert retrieval model*, he proposed that the repeated covert retrieval opportunities afforded by complex span tasks create stronger retrieval cues for that information after a delay than do simple span tasks. Specifically, participants appear to covertly retrieve to-be-remembered items during the pauses after completing the processing phases of the complex span task (e.g., the arithmetic problem in the operation span), facilitating long-term retention. Such data comport with other studies showing that retrieval practice in WM contributes to long-term retention (Loaiza, McCabe, Youngblood, Rose, & Myerson, 2011; Rose, Myerson, Roediger, & Hale, 2010). However, the nature of these covert retrieval attempts remains unclear.

Given that the processing phases of a complex span task disrupt the maintenance of information, attentionally refreshing information may be the mechanism that underlies the delayed recall effect predicted by the covert retrieval model (cf. Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007). Furthermore, attentional refreshing may encourage retrieval cues corresponding to the original order of presented information within a trial (i.e., temporal–contextual cues). Accordingly, McCabe (2008) reported that items at the beginning of trials from a complex span task were most likely to be recalled after a delay. Such items, presented early in the task, likely have more opportunities to be covertly retrieved via attentional refreshing. Thus, the original temporal context of a representation may be more likely to be bound to its respective representation with repeated attentional refreshing during WM encoding (cf. Chalfonte & Johnson, 1996). Others have also demonstrated the influence of attentional refreshing and temporal associations formed in WM on episodic memory (Johnson et al., 2002; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000). For example, Johnson et al. have shown that refreshing predicts episodic memory more strongly in younger than in older adults. Kahana and colleagues have also shown that temporal associations made between items and their respective serial positions during encoding strongly predict episodic memory performance (Kahana, Howard, Zaromb, & Wingfield, 2002; Sederberg, Miller, Howard, & Kahana, 2010). This suggests that attentional refreshing in WM promotes long-term retention and that the original temporal context is likely to be used as a retrieval cue to access item-specific information after a delay. Thus, the covert retrieval model predicts that (1) covert retrieval opportunities are, more specifically, opportunities to attentionally refresh previously presented information, and (2) if an item is attentionally refreshed, it is more likely to be stably bound to its original temporal context. Such durable binding will be evident if episodic memory retrieval is facilitated by cues from the original context of the encoding phase.

By contrast, simple span task encoding may not encourage the use of temporal–contextual cues during retrieval from episodic memory, because there is little opportunity to attentionally refresh these content–context bindings during encoding (i.e., there are no processing phases interpolated between the items to serve as pauses that could afford opportunities for attentional refreshing).

McCabe (2008) provided evidence for this by demonstrating that delayed recall of items presented during simple span tasks does not differ as a function of initial serial position. Thus, the original temporal context of representations studied under simple span task conditions is a less useful cue after a delay, because simple span task conditions do not afford attentional refreshing opportunities to strengthen the association between an item and its temporal context. However, McCabe's simple span task only included between two and four words to remember (i.e., subspan list lengths). Data have suggested that the retrieval both of longer trial lengths in simple span tasks (i.e., supraspan list lengths of more than four words to remember) and of lists in complex span tasks requires a cue-dependent search of recently maintained representations that have been displaced from the focus of attention (Unsworth & Engle, 2006, 2007). Thus, complex span tasks and supraspan list lengths in simple span tasks may similarly engage the temporal–contextual processing necessary to recall information in WM that is no longer active. The present study tested this hypothesis by comparing sub- and supraspan list lengths in a simple span task to complex span recall.

One way to investigate temporal–contextual processing during WM encoding is to examine recall after a delay (i.e., information is no longer active in WM). Specifically, if a WM task encourages content–context binding during encoding, perhaps due to repeated attentional refreshing, making temporal–contextual cues available after a delay should provide access to those representations. This would suggest that retrieval from episodic memory is most effective when cues emphasize the original encoding conditions (cf. Thomson & Tulving, 1970). Likewise, for tasks that do not encourage content–context binding during encoding, perhaps due to a lack of attentional refreshing opportunities, providing temporal–contextual cues after a delay should benefit performance less, due to the mismatch between the original encoding and retrieval conditions (Thomson & Tulving, 1970). Thus, investigating whether temporal–contextual cuing is evident in episodic memory should demonstrate whether recall from both supraspan list lengths in simple span and complex span tasks (Unsworth & Engle, 2006, 2007) reflects similarly durable content–context bindings. Although attentional refreshing is typically examined within tests of WM (e.g., Barrouillet et al., 2004; Barrouillet et al., 2007; Camos et al., 2009; Camos et al. 2011), the present study investigated the consequences of attentional refreshing by examining patterns in episodic memory that indicate whether temporal–contextual cues differentially guide retrieval. This result would support the prediction that temporal–contextual processing is a consequence of content–context bindings created during WM encoding (Oberauer, 2005, 2009), facilitating understanding of how operations during WM influence access to information in episodic memory (Johnson et al., 2002; Kahana et al., 2002; McCabe, 2008; Sederberg et al., 2010).

Overview of the present experiments

The first two experiments investigated the efficacy of temporal–contextual cues that were either provided (Experiment 1) or generated by the participant (Experiment 2) during an episodic memory test for items originally studied during simple and complex span tasks. We also investigated alternative explanations of these data by varying the number of attentional refreshing opportunities during a modified complex span task in Experiment 3. Experiments 1 and 2 included three different trial types: operation span (i.e., complex span) trials, subspan word span trials (i.e., four items to recall), and supraspan word span trials (i.e., eight items to recall). However, delayed recall based on temporal–contextual associations was measured differently in each experiment. In Experiment 1, delayed cued recall was examined by cuing items from the span tasks with the adjacent item from a given trial. Thus, successful recall required access to the temporal context from span task encoding. In Experiment 2, a delayed free recall test was given and a *conditional response probability as a function of lag* (lag-CRP) analysis (Kahana, 1996) was used to examine whether temporal–contextual processing differed for the three trial types. A lag-CRP analysis determines the likelihood that items from adjacent serial positions at encoding will be recalled together. Prior work has suggested that recall of items from adjacent serial positions resulted from reinstatement of the temporal–contextual associations from study (see Kahana, Howard, & Polyn, 2008, for a review). To anticipate the results, delayed recall was superior following complex span relative to simple span tasks. Experiment 3 tested whether, alternatively, enhanced delayed recall for items studied during operation span was due to temporal distinctiveness or to spaced learning, by varying the presentation of the arithmetic problems within a trial.

Experiments 1 and 2 allowed us to test several predictions concerning temporal–contextual processing during encoding in WM. Namely, providing temporal–contextual cues during an episodic memory test should afford better access to items from a task that emphasizes content–context binding during encoding than to those from a task that does not. McCabe (2008) demonstrated that the likelihood of accessing content–context bindings is strongly related to providing attentional refreshing opportunities. Thus, we expected to replicate the delayed recall effect

(McCabe, 2008) using temporal–contextual cues, such that items originally studied during an operation span task would be better retrieved using temporal–contextual cues after a delay than would items from subspan word span trials. In addition, by including supraspan word span trials, we assessed whether the common variability between complex span and simple span tasks reflects similar temporal–contextual processing during encoding (Unsworth & Engle, 2006, 2007). Given that supraspan list lengths in word span tasks do not afford attentional refreshing opportunities, we expected that temporal–contextual cues would not benefit delayed recall for items from supraspan list lengths in word span as compared to items studied during operation span. This would suggest that, although complex span and supraspan list lengths of simple span are strongly related (Unsworth & Engle, 2006), the source of common variance is not similar degrees of temporal–contextual processing. Experiment 3 allowed us to adjudicate between different explanations of temporal–contextual processing in complex span tasks as the product of either spacing or the number of attentional refreshing opportunities provided.

Experiment 1

The goal of Experiment 1 was to establish the role of temporal–contextual processing during simple and complex span task encoding. This was done using temporal–contextual cues after a delay, such that items of a particular trial were cued by items from neighboring serial positions from the original study phase. For example, if participants studied the words “heat, clothes, park, sky,” they would later be asked, “HEAT came before the word _____” during the delayed test. We expected to replicate the delayed recall effect (McCabe, 2008), such that delayed cued recall for operation span items would exceed recall for sub- and supraspan list lengths of word span. This would indicate that providing temporal–contextual cues after a delay elicited content–context bindings created during WM encoding.

Method

Participants A group of 30 participants (16 female, 14 male; age: $M = 19.90$ years, $SD = 2.58$) from introductory psychology courses at Colorado State University participated in exchange for course credit.

Materials and procedure Participants first completed 30 multiplication practice problems (e.g., 6 × 4 = 24?; 7 × 8 = 55?) in order to familiarize themselves with the processing component of the operation span task. Next, participants completed six randomized blocks, with one operation span trial (four to-be-remembered words), one subspan word span trial (four to-be-remembered words), and one supraspan word span trial (eight to-be-remembered words) randomly presented in each block.

The to-be-remembered stimuli for all tasks were concrete, high-frequency nouns: log HAL frequency ratings ranged from 7.42 to 12.67 ($M = 10.50$, $SD = 0.86$), with a range of 3–9 letters ($M = 5.10$, $SD = 1.25$) and a range of 1–2 syllables ($M = 1.33$, $SD = 0.47$). Participants were instructed to study the words in each trial silently. On each operation span trial, participants read aloud and responded to a multiplication problem within 3,500 ms, and the experimenter recorded their response. Half of the problems had correct answers, and half had incorrect answers. After each problem, a word was presented for 1,000 ms. Subspan word span trials included four to-be-remembered words presented for 1,000 ms each, and supraspan word span trials included eight to-be-remembered words presented for 1,000 ms each. All trials ended with a cue to prompt recall of the words in the order that they had been presented.

After the first block of three trials, a demographics questionnaire was given and timed for each participant, in order to allot the same amount of time for each successive block delay thereafter. This was done to ensure that the timing of the delayed tasks was constant across blocks ($M = 101$ s, $SD = 20$, range = 75–150 s; differences in the delays across subjects did not impact or interact with the effect of trial type on delayed cued recall, $F\text{s} \leq 1.19$, $ps \geq .38$). Participants completed word searches for the delays following the remaining blocks. After each distractor task, a delayed cued recall test was given for the items from the most recently presented block, with 8 (2 operation span, 2 subspan word span, and 4 supraspan word span) of the 16 originally studied words randomly cued one at a time onscreen using temporal–contextual cues (e.g., “HEAT came before the word _______”). Only the even serial positions of each trial were cued, because the first word could not be cued in this manner (i.e., no word preceded the first serial position), and the rest of the odd serial positions could not be unique answers while also serving as cues. For the analysis of the results, immediate recall and delayed cued recall were collapsed across the six blocks.

Results

All of the reported significant results met a criterion of $p < .05$, and mean square error (*MSE*) and partial eta squared (η_p^2) are reported for all F values >1. Although participants were instructed to immediately recall the items as they were originally presented, we also scored performance according to “free recall” methods, such that recalled items were scored as correct, regardless of serial output. We used immediate free recall instead of serial recall in order to maintain consistency between the two experiments, but we note that all analyses were the same between the serial and free recall scoring methods (see Table 1). In addition, we included recall of the first four items of supraspan list lengths in word span in the following analyses so as to ascertain whether temporal–contextual processing occurs for items that are predicted to require reactivation into the focus of attention for retrieval from WM (Unsworth & Engle, 2006, 2007). Recall scores for each participant were converted into proportions of the total number of items to remember (i.e., four or eight) for each trial type, in order to facilitate comparisons between trial types. In addition, we conducted separate one-way ANOVAs for immediate free recall and delayed cued recall, because the difference in retrieval methods did not permit us to examine recall as a fully crossed factor.

A one-way ANOVA (trial type: operation span, subspan word span, or supraspan word span) on immediate free recall indicated a significant main effect of trial type, $F(2, 58) = 240.90$, $MSE = .01$, $\eta_p^2 = .89$ (see Table 1). The same one-way ANOVA for recall of the first four items of the supraspan word span trials, instead of all eight items, yielded a similar result, $F(2, 58) = 55.25$, $MSE = .01$, $\eta_p^2 = .66$. Planned comparisons revealed that immediate recall was greater for items from subspan word span than for items from operation span, $F(1, 29) = 133.63$, $MSE = .01$, $\eta_p^2 = .82$, items from supraspan list lengths of word span, $F(1, 29) = 678.83$, $MSE = .01$, $\eta_p^2 = .96$, and the first four items from supraspan list lengths of word span, $F(1, 29) = 71.88$, $MSE = .01$, $\eta_p^2 = .71$. Furthermore, immediate recall was greater for items from operation span than for supraspan list lengths of word span, $F(1, 29) = 79.99$, $MSE = .01$, $\eta_p^2 = .73$, but it did not differ from recall for the first four items from supraspan list lengths of word span, $F < 1$.

More importantly, we also compared delayed cued recall across trial types in order to examine the influence of reinstating temporal–contextual cues. A one-way ANOVA (trial type: operation span, subspan word span, or supraspan word span) yielded a main effect of trial type, $F(2, 58) = 10.24$, $MSE = .01$, $\eta_p^2 = .26$ (see Fig. 1). A similar one-way ANOVA with the first four items of supraspan word span included instead of all eight items yielded a similar result, $F(2, 58) = 7.60$, $MSE = .02$, $\eta_p^2 = .21$. In contrast to immediate recall, delayed cued recall was more successful for operation span items than for subspan word span items, $F(1, 29) = 8.70$, $MSE = .02$, $\eta_p^2 = .23$, and supraspan word span items, $F(1, 29) = 15.69$, $MSE = .02$, $\eta_p^2 = .35$. Delayed cued recall was also greater for operation span items than for the first four items from supraspan list lengths of word span, $F(1, 29) = 9.86$, $MSE = .02$, $\eta_p^2 = .25$. Furthermore, supraspan word span delayed cued recall did not differ from subspan word span performance, $F(1, 29) = 1.42$, $MSE = .01$, $\eta_p^2 = .05$. This result was obtained even when considering performance for the first four items from the supraspan list length trials of word span, $F < 1$, which putatively required temporal–contextual processing during encoding (Unsworth & Engle, 2006).

Discussion

The data reported in Experiment 1 replicated the delayed recall effect (McCabe, 2008) using a delayed cued recall paradigm. That is, information studied in a complex span task was more likely to be retrieved during tests of episodic memory than was information studied in a simple span task, regardless of the number of items to remember from the simple span tasks (i.e., four or eight items). These data support the hypothesis that WM encoding involves binding a representation to a source context (McCabe, 2008; Oberauer, 2009). In addition, these data indicate that supraspan list lengths in simple span tasks do not engage temporal–contextual processing during encoding similar to that for complex span tasks. This may be due to the relative lack of attentional refreshing opportunities in simple span tasks of any list length (cf. McCabe, 2008). Thus, although supraspan list lengths of simple span tasks and complex span tasks are strongly related (Unsworth & Engle, 2006, 2007), the source of their common variability does not

Table 1 Immediate recall performance for Experiments 1 and 2 as a function of trial type and scoring method

	Experiment 1		Experiment 2	
	Serial Recall Scoring	Free Recall Scoring	Serial Recall Scoring	Free Recall Scoring
Operation span trials	.58 (.21)	.74 (.11)	.44 (.26)	.71 (.16)
Subspan word span trials	.96 (.07)	.98 (.04)	.92 (.14)	.97 (.06)
Supraspan word span trials	.33 (.13)	.55 (.08)	.26 (.12)	.54 (.11)
First four items of supraspan word span trials	.59 (.20)	.72 (.16)	.49 (.21)	.65 (.16)

Standard deviations are in parentheses

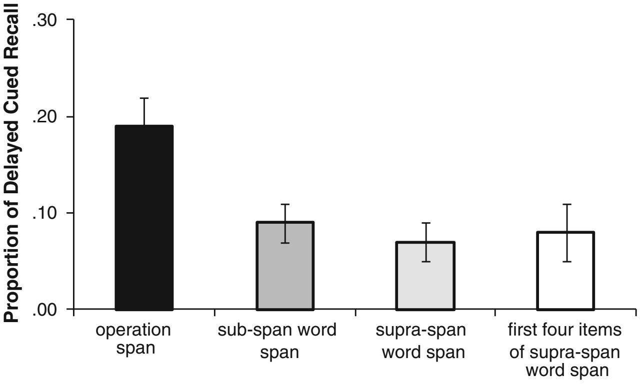

Fig. 1 Delayed cued recall performance as a function of trial type in Experiment 1. Error bars represent one standard error of the mean

appear to be common temporal–contextual processing during encoding. We sought to provide converging support for these findings by decomposing patterns of delayed free recall in Experiment 2.

Experiment 2

The purpose of Experiment 2 was to further identify the nature of the temporal associations that facilitate delayed free recall from complex span as compared to recall from simple span tasks. Kahana and colleagues (Howard & Kahana, 1999, 2002; Kahana, 1996) have suggested that maintenance of temporal context can be ascertained by plotting output order in free recall according to the original presentation order at encoding. This measure, referred to as the "lag-CRP", represents the distance, or *lag*, between two successively recalled items that had been presented during study. For example, if a list originally contained the words *window*, *husband*, and *apple*, recalling first *window* and then *husband* would have a forward lag of +1, or recalling *window* and then *apple* would have a forward lag of +2. Recalling *apple* and then *husband* would have a backward lag of −1, and so on. Previous research has suggested that temporal associations made between items during encoding predict delayed recall (Kahana et al., 2002; Sederberg et al., 2010). However, to our knowledge, no study has used lag-CRP analyses to investigate the temporal associations between items studied during complex and simple span tasks. Experiment 2 utilized measures of lag-CRP for immediate and delayed free recall of items studied during complex span, as well as during sub- and supraspan list lengths of simple span, in order to elucidate the nature of the temporal associations made during WM encoding. We anticipated that, consistent with Experiment 1, participants would be more likely to exhibit temporal associations between items presented in the operation span task relative to sub- and supraspan list lengths of word span.

Method

Participants A group of 30 individuals (17 female, 13 male; age: M = 19.23 years, SD = 1.76) participated in exchange for partial course credit. None of them had participated in Experiment 1.

Materials and procedure The materials and procedure were identical to those of Experiment 1, except that a delayed free recall test followed each of the six blocks instead of a delayed cued recall test. During the delayed tests, participants were instructed to recall as many items as possible, regardless of their original order of presentation or the trial in which they were presented. The delay following each block was constant for each participant (M = 99 s, SD = 28, range = 46–163 s; differences in the delays across subjects did not impact or interact with the effect of trial type on delayed free recall, $F\text{s} \leq 1.35$, $ps \geq .27$).

Results

Overall immediate and delayed recall performance Because both tests involved free recall, we first compared overall delayed recall (Fig. 2) with immediate free recall (Table 1). A 2 (time of recall: immediate or delayed) × 3 (trial type: operation span, subspan word span, or supraspan word span) repeated measures ANOVA showed that, overall, immediate recall was superior to delayed recall, $F(1, 29) = 778.88$, $MSE = .02$, $\eta_p^2 = .96$. Furthermore, there was an overall effect of trial type on recall, $F(2, 58) = 61.19$, $MSE = .01$, $\eta_p^2 = .68$. The interaction between time of test and trial type was also significant, $F(2, 58) = 121.37$, $MSE = .01$, $\eta_p^2 = .81$. Thus, although immediate recall was best for items from subspan word span trials as compared to operation span and supraspan word span items, delayed free recall was greater for operation span items than for either

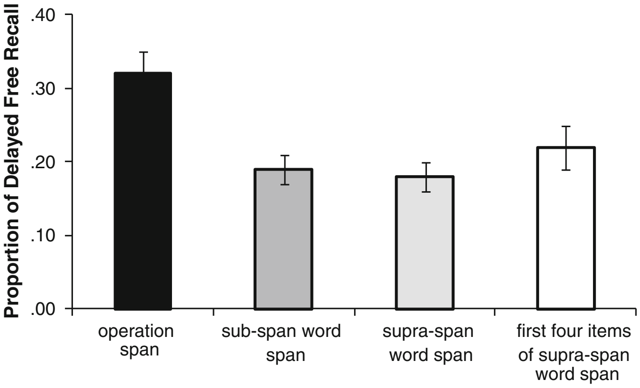

Fig. 2 Delayed free recall performance as a function of trial type in Experiment 2. Error bars represent one standard error of the mean

subspan word span items, $F(1, 29) = 18.60$, $MSE = .01$, $\eta^2_p = .39$, or supraspan word span items, $F(1, 29) = 28.70$, $MSE = .01$, $\eta^2_p = .50$. A similar analysis that included the first four items of the supraspan word span trials instead of performance for all eight items yielded similar results: a main effect of time of recall, $F(1, 29) = 589.48$, $MSE = .02$, $\eta^2_p = .95$, a main effect of trial type, $F(2, 58) = 18.08$, $MSE = .02$, $\eta^2_p = .38$, and a significant interaction between the two, $F(2, 58) = 69.31$, $MSE = .01$, $\eta^2_p = .71$. Thus, operation span delayed recall was also greater than delayed recall for the first four items of the supraspan word span trials, $F(1, 29) = 8.17$, $MSE = .02$, $\eta^2_p = .22$. Furthermore, delayed recall from the subspan and supraspan word span trials did not differ, even when comparing recall for the first four items of the supraspan trials and the subspan trials of word span, *F*s < 1.

Lag-CRP analyses for immediate recall performance For the lag-CRP analysis of immediate and delayed free recall, only proportions from lags of up to ±3 for each trial type were assessed, for the sake of brevity (see Farrell & Lewandowsky, 2008, for a discussion of recall for longer lags). The only trial type to have a larger lag than ±3 was the supraspan list lengths of word span, which could conceivably have recall lags up to ±7. These proportions were not assessed, but comprised only 9% of the responses for supraspan simple immediate recall, and less than 2% of responses for supraspan simple delayed recall, which are the critical data for the present purposes. The data used in the lag-CRP analyses were proportions of the overall immediate and delayed recall reported. For example, for the operation span trials and subspan word span trials, there were three opportunities during each trial to recall items with a +1 and a −1 lag, whereas there were only two opportunities to recall items with a +2 and a −2 lag, and so on. In addition, recall between trial types (e.g., recalling an operation span item and then a word span item) did not count toward the lag-CRP analyses.

Figure 3 displays the lag-CRP analysis for immediate recall. In terms of forward associations (positive lags) in immediate recall, subspan word span items were the most likely to be recalled at lags of +1, as compared to operation span items, $F(1, 29) = 98.81$, $MSE = .04$, $\eta^2_p = .77$, supraspan word span items, $F(1, 29) = 631.35$, $MSE = .01$, $\eta^2_p = .96$, and the first four items of supraspan word span trials, $F(1, 29) = 141.75$, $MSE = .03$, $\eta^2_p = .83$. However, items from subspan word span trials were less likely to be recalled than operation span items at +2 lags, $F(1, 29) = 10.26$, $MSE = .01$, $\eta^2_p = .26$, and +3 lags, $F(1, 29) = 14.77$, $MSE = .01$, $\eta^2_p = .34$. Interestingly, recall of operation span items was not significantly different from recall of the first four items of the supraspan word span trials at lags of +1, $F < 1$, and +2, $F(1, 29) = 2.05$, $MSE = .01$, $\eta^2_p = .07$.

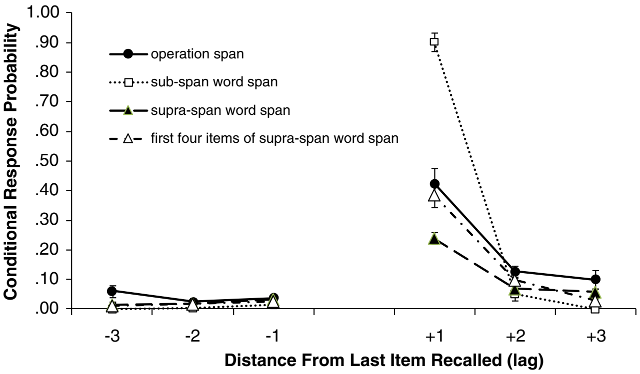

Fig. 3 Conditional response probability curves for immediate free recall as a function of trial type in Experiment 2. Error bars represent one standard error of the mean. Note that supraspan list length trials of simple span only show the lag up to ±3 for the sake of brevity

Lag-CRP analyses for delayed recall performance The critical data for examining temporal–contextual associations after a delay involved lag-CRP for delayed free recall (see Fig. 4). We were particularly interested in differences in delayed recall between operation span and word span trials as a function of lag-CRP. Forward associations were more likely for operation span items than for subspan word span items, particularly for lags of +1, $F(1, 29) = 6.26$, $MSE = .01$, $\eta^2_p = .18$. This was also the case when comparing operation span items at lag +1 to supraspan word span items, $F(1, 29) = 28.90$, $MSE = .01$, $\eta^2_p = .50$, and the first four items of the supraspan word span trials, $F(1, 29) = 20.91$, $MSE = .01$, $\eta^2_p = .42$. Operation span items were also more likely to be recalled at lags of +2 than

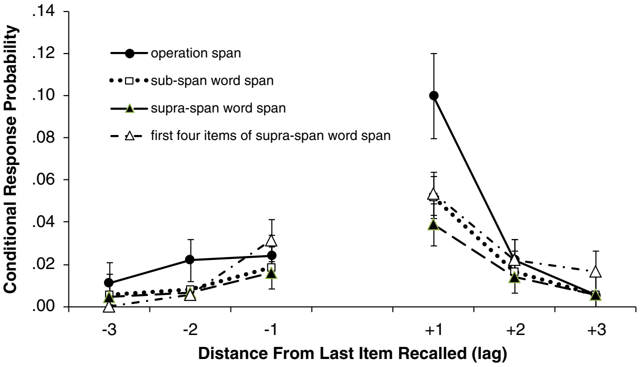

Fig. 4 Conditional response probability curves for delayed free recall as a function of trial type in Experiment 2. Error bars represent one standard error of the mean. Note that supraspan list length trials of simple span only show the lag up to ±3 for the sake of brevity

were supraspan word span items, $F(1, 29) = 5.55$, $MSE = .01$, $\eta^2_p = .16$.

Discussion

Findings from Experiment 2 converged with those of Experiment 1 in showing that delayed recall of operation span items was greater than performance for sub- and supraspan list lengths of word span, replicating the delayed recall effect (McCabe, 2008). Critically, the lag-CRP data indicated that maintenance of temporal associations after a delay was greater for operation span items than for either subspan or supraspan word span items. These results are consistent with the prediction that content–context bindings are strengthened by attentionally refreshing information in WM. These data also converged with Experiment 1 in demonstrating that temporal associations made during simple span task encoding of any list length were not evident in delayed recall, suggesting that attentional refreshing opportunities are important for establishing content–context bindings in WM (McCabe, 2008). Thus, although temporal–contextual associations were evident in lag-CRP analyses of subspan word span items in immediate recall, these associations were not accessible during retrieval from episodic memory, presumably because there were no opportunities to reinforce the content–context bindings using attentional refreshing.

Experiment 3

Data from Experiments 1 and 2 comported with the hypothesis that attentionally refreshing information in WM supports long-term retention. However, alternatives to the attentional-refreshing hypothesis could also potentially explain the data, including a temporal-distinctiveness account and a spaced-learning account. We examined these possibilities in Experiment 3 by modifying the traditional operation span task with the goal of varying the attentional refreshing demands of the task.

First, the nature of complex span tasks, with a processing task interspersed between each to-be-remembered word, may render it such that complex span items are more temporally discriminable from one another than are simple span items. Indeed, some evidence has suggested that recall of information from WM and episodic memory may be due to the temporal distinctiveness of information (G.D.A. Brown, Neath, & Charter, 2007; Glenberg & Swanson, 1986). Thus, according to this *temporal-distinctiveness account*, complex span items may be more retrievable from episodic memory because they were presented in a more temporally discriminable manner than simple span items.

A corollary of this argument is that *spaced learning* may account for the aforementioned data. That is, complex span items may be more likely to be recalled because they were presented in a distributed fashion, as compared to the relatively massed presentation of simple span trials. Spaced learning has long been shown to improve long-term memory retrieval (Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006), and thus the results of Experiments 1 and 2 could reflect the schedule of presentation, rather than the number of refreshing opportunities.

To address these differing accounts, in Experiment 3 we varied the presentation of the to-be-remembered items while holding all other factors constant. Specifically, we held the number of arithmetic problems to be solved constant, but varied the number of potential attentional refreshing opportunities (between zero and three opportunities). The design for this experiment involved three different trial types: *spaced retrieval*, *words last*, and *words first*. The latter two conditions both involved massed study, but differed in terms of the number of potential attentional refreshing opportunities.

Figure 5 illustrates the procedure for each trial type in Experiment 3. The spaced-retrieval trials were typical operation span trials, with an arithmetic problem preceding each to-be-remembered word. Thus, attentional refreshing opportunities decreased for later serial positions (cf. McCabe, 2008). In the words-last condition, the arithmetic problems were completed first, followed by presentation of all of the to-be-remembered items. Because of this manipulation, the maintenance demands of the words-last trial were essentially identical to a word span task (i.e., words were recalled immediately after being presented in a massed fashion). The words-first trials mimicked a version of a Brown–Peterson type task (J. Brown, 1958; Peterson & Peterson, 1959), such that presentation of the to-

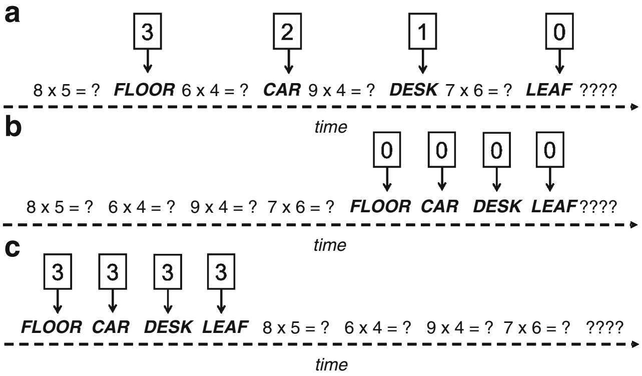

Fig. 5 An illustration of the three trial types included in Experiment 3: (**a**) spaced retrieval, (**b**) words last, and (**c**) words first. Note that the words-last and words-first conditions involve massed presentation, whereas the spaced-retrieval condition involves spaced presentation. The number markers indicate the number of attentional refreshing opportunities afforded by the trial for each serial position

be-remembered items was massed, but this was followed by completion of all of the arithmetic problems. Therefore, although the items in the words-first trials were massed, these items actually had more attentional refreshing opportunities overall than in the spaced-retrieval trials.

An analysis of delayed recall as a function of initial serial position during the span task will be informative with respect to adjudicating between accounts of the delayed recall effect. We have suggested that attentional refreshing supports long-term retention by encouraging content–context bindings in WM that can be accessed during episodic memory. If this is the case, delayed recall should be greatest and relatively stable across serial positions in the words-first condition, because all four of the to-be-remembered items had three opportunities to be attentionally refreshed. In the spaced-retrieval condition, the number of attentional refreshing opportunities declined as a function of serial position (cf. McCabe, 2008), and thus delayed recall should decrease as a function of initial serial position. For the words-last condition, we expected delayed recall to be poorest because those to-be-remembered items had no opportunity to be attentionally refreshed. However, according to the temporal-distinctiveness and spaced-learning accounts, delayed recall should be poorest for the words-first and words-last conditions relative to the spaced-retrieval condition, because the items in the spaced-retrieval trials are more temporally distinct and provide spaced learning opportunities as compared to the massed conditions. These alternative accounts also predict that recall from the words-first and words-last conditions should not differ significantly, because the presentation formats were similarly massed.

Method

Participants A group of 47 individuals (27 female, 20 male; age: M = 19.00 years, SD = 2.09) participated in exchange for partial course credit. None of the participants had participated in the prior experiments.

Materials and procedure Participants completed the same practice arithmetic task described in Experiments 1 and 2. Afterward, all participants completed the three different span task trial types, four of each type, randomly intermixed. The three trial types included spaced-retrieval trials, words-last trials, and words-first trials (see Fig. 5). There were always four words to remember in every trial, and there were four arithmetic problems to be solved; the only difference between the trials was the schedule of presentation for the to-be-remembered words and the arithmetic problems. The arithmetic problem of each trial was presented onscreen in its entirety for 3,500 ms; participants read the problem aloud and responded as they had done in the previous experiments. At the end of each trial, participants were prompted to recall the words in the order that they had been presented. After all trials were presented, participants completed an unrelated task for several minutes. Afterward, participants were instructed to recall as many items from the original trials as possible, without regard to the original order of presentation. As in Experiments 1 and 2, immediate free recall was used in the analyses to compare to delayed free recall (cf. McCabe, 2008).

Results and discussion

In order to examine whether the delayed recall effect occurred for both the spaced-retrieval and words-first conditions (as compared to the words-last condition), we began by conducting a 2 (time of test: immediate or delayed) × 3 (trial type: words last, spaced retrieval, or words first) repeated measures ANOVA (see Fig. 6). This initial analysis revealed a main effect of time of test, $F(1, 46) = 2{,}226.93$, $MSE = .01$, $\eta_p^2 = .98$, a main effect of trial type, $F(2, 92) = 16.54$, $MSE = .03$, $\eta_p^2 = .26$, and a significant interaction, $F(2, 92) = 186.76$, $MSE = .01$, $\eta_p^2 = .80$. A closer examination of the immediate recall data indicated that, relative to the words-last trials, participants recalled fewer spaced-retrieval, $F(1, 46) = 128.19$, $MSE = .01$, $\eta_p^2 = .74$, and words-first, $F(1, 46) = 207.80$, $MSE = .02$, $\eta_p^2 = .82$, items. As well, participants recalled fewer words-first items than spaced-retrieval items, $F(1, 46) = 46.58$, $MSE = .03$, $\eta_p^2 = .50$. In contrast, for delayed recall, participants recalled more spaced-retrieval items than words-last items, $F(1, 46) = 27.38$, $MSE = .02$, $\eta_p^2 = .37$, replicating the delayed recall effect for operation span trials. The words-first trials also showed greater delayed recall than did the words-last trials, $F(1, 46) = 33.18$, $MSE = .02$, $\eta_p^2 = .42$. However, there was no significant difference in

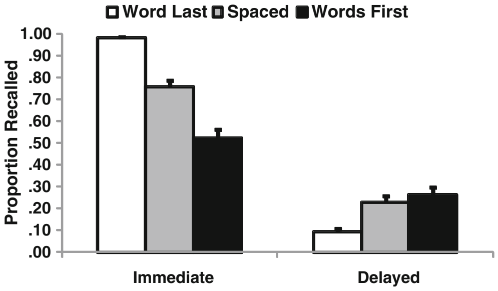

Fig. 6 Immediate (span task) and delayed recall for items processed during the words-last (word span), spaced-retrieval (operation span), and words-first conditions of the span task in Experiment 3. Bars represent one standard error of the mean

delayed recall for the spaced-retrieval and words-first trials, $F < 1$. This finding is inconsistent with the temporal-distinctiveness and spaced-learning explanations of the delayed recall effect. That is, episodic memory performance did not depend on whether to-be-remembered items were presented in massed or spaced formats. However, these data do not necessarily provide strong support for the attentional-refreshing hypothesis either, because items in the words-first trials had more attentional refreshing opportunities than did those in the spaced-retrieval trials, but delayed recall did not differ significantly for these trial types. In order to more thoroughly examine the influence of the number of attentional refreshing opportunities on long-term retention, we conducted a fine-grained analysis of delayed recall as a function of the initial serial position of to-be-remembered items during the span tasks.

Delayed recall as a function of initial serial position during the span task According to the attentional-refreshing hypothesis, delayed recall should decrease as a function of initial serial position on the span task for the spaced-retrieval trials, replicating McCabe (2008). That is, because later serial positions afford fewer refreshing opportunities, delayed recall should be poorer for items in later serial positions for spaced-retrieval trials. However, all of the to-be-remembered items in the words-first trials were followed by four arithmetic problems. Thus, each of those items had three attentional refreshing opportunities after completion of the subsequent arithmetic problems, and should show roughly equivalent delayed recall as a function of initial serial positions. In the words-last trials, the to-be-remembered items had no attentional refreshing opportunities, and thus there should also be roughly equivalent delayed recall as a function of initial serial positions, though the overall level of delayed recall should be considerably lower than in the words-first or spaced-retrieval trials.

In order to test these hypotheses regarding the effect of the initial serial position of to-be-remembered items during the span task on delayed recall, we conducted regression analysis that assessed the influences of trial type and serial position on delayed recall. We first coded delayed recall according to the serial position and aggregated across each serial position for each trial type. We then dummy-coded trial type, such that two dummy-coded variables were created with spaced retrieval as the reference variable (words last and words first as the dummy-coded variables). We examined whether these dummy-coded variables for trial type would interact with serial position, such that the intercepts and slopes predicting delayed recall across serial positions would differ for each trial type. As Table 2 shows, including interaction terms in a model predicting delayed recall significantly improved the variance accounted for by the model relative to models that only included the effects of the individual independent variables. Thus, the regression equations of each trial type were significantly different. Figure 7 shows the aggregate performance across serial positions for each trial type, with each individual trial type's regression equation listed alongside the trial name. Although the slopes of the words-first and words-last trials were slightly negative, the source of the interaction was due to the significantly more negative slope of the spaced-retrieval trial type. Indeed, when excluding spaced-retrieval performance from the analysis, the model with the interaction terms no longer significantly improved the model fit, F change < 1. This suggests that delayed recall significantly decreased with successive serial positions in the spaced-retrieval condition, while recall from the words-first and words-last conditions was relatively stable across serial positions.

Manipulating the number of attentional refreshing opportunities thus had strong effects on delayed recall. This comports with the prediction that attentional refreshing promotes content–context bindings during WM encoding, evident in greater delayed recall as attentional refreshing opportunities increased. In order to test this more directly, we examined delayed recall as a function of the attentional refreshing opportunities afforded in each trial (cf. McCabe,

Table 2 Regression analyses predicting delayed recall in Experiment 3

Model	Variable	B	SE	β	R^2	F	ΔF
1	Words last	–.14	.05	−0.70			
	Words first	.03	.05	0.17	.63	7.78^{*}	
2	Words last	–.14	.03	−0.70			
	Words first	.03	.03	0.17			
	Serial position	–.04	.01	−0.50	.88	19.34^{**}	16.19^{**}
3	Words last	–.28	.04	−1.40			
	Words first	–.09	.04	−0.43			
	Serial position	–.08	.01	−0.91			
	Words last × Serial position	.06	.02	0.80			
	Words first × Serial position	.05	.02	0.68	.97	32.78^{**}	7.30^{*}

The spaced-retrieval condition was the reference variable for the two dummy-coded variables (words last and words first).
$^{*}p < .05$, $^{**}p < .01$

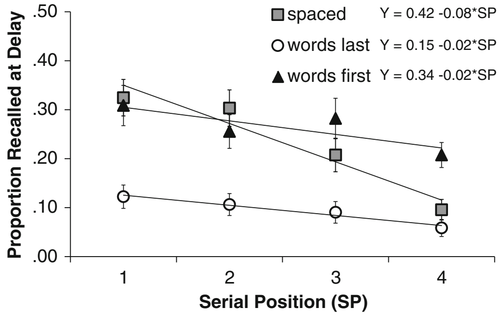

Fig. 7 Delayed recall as a function of initial serial position during the span task for the words-last, spaced-retrieval, and words-first conditions of the span task in Experiment 3. The regression equation for each trial type is shown alongside the trial name. Bars represent one standard error of the mean

2008). Figure 5 shows that the number of attentional refreshing opportunities varied between each trial type for each serial position. The number of attentional refreshing opportunities decreased with successive serial positions in the spaced-retrieval trials according to the number of arithmetic problems that served as pauses between the presentations of the items. In the words-first condition, the number of attentional refreshing opportunities was the same for each serial position, since the arithmetic problems followed the presentation of all four words. Finally, in the words-last trial, the number of attentional refreshing opportunities was always zero for all four serial positions, because no arithmetic problems followed the words. We coded delayed recall of the items according to the number of attentional refreshing opportunities across trial types and then averaged across participants for each opportunity. The aggregate correlation between the number of attentional refreshing opportunities and delayed recall in Experiment 3 was .90 (consistent with the data reported by McCabe, 2008, using only operation span trials). This correlation obtains (and even marginally improves) when holding trial type constant, r = .95.

General discussion

The goal of the present study was to determine whether attentional refreshing in WM enhances binding of items to source contexts. This was done by examining patterns of retrieval in episodic memory that reflect access to the original source contexts. The results indicated that retrieval based on temporal associations was more effective for tasks that afforded attentional refreshing opportunities, evident in delayed cued recall (Experiment 1) and delayed free recall (Experiments 2 and 3). In Experiments 1 and 2, delayed recall for operation span was superior to recall for subspan word span. Critically, supraspan list length word span trials did not show the same pattern of delayed performance as operation span, although similar immediate recall patterns were evident. This is inconsistent with the idea that simple and complex span tasks engage identical maintenance processes (Unsworth & Engle, 2007). Furthermore, Experiment 3 showed that the delayed recall effect cannot be attributed to temporal distinctiveness or to spaced learning. These findings have a number of implications regarding the processes involved in WM and, in part, address how information processed in WM becomes available to long-term episodic memory.

Implications for models of WM

The covert retrieval model (McCabe, 2008) suggests that the processes underlying complex span tasks are distinct from those underlying simple span tasks of any list length, due to the retrieval cues that are instantiated during covert retrieval of complex span items during the encoding phase. We built upon this notion by demonstrating that opportunities afforded in-between presentations of the processing element of the task and the to-be-remembered items allow participants to attentionally refresh previously studied information in order to effectively maintain and retrieve the items for immediate recall (cf. Barrouillet et al., 2004). The act of attentional refreshing requires selection of less activated information. As opportunities for refreshing information increase, the more reliably the original temporal context of a representation can serve as a cue for episodic memory retrieval. Although temporal–contextual processing of simple span items was evident in immediate recall, particularly in Experiment 2, these temporal–contextual cues were not available at a delay for simple span items of any list length, because there was little opportunity to attentionally refresh these items during encoding. Thus, the original temporal context of simple span items is a poor cue during retrieval from episodic memory. Such findings suggest that the common source of variance between complex span and supraspan list lengths of simple span (cf. Unsworth & Engle, 2006) may reflect some factor other than temporal–contextual processing during encoding.

Although the present study does not unequivocally elucidate the maintenance mechanisms operating in simple span tasks or the source of the relation between supraspan simple span and complex span tasks, future research should investigate these issues. Furthermore, it is unclear whether elaborative rehearsal may also enhance long-term retention of complex span items as compared to simple span items. It has long been shown that deeper encoding strategies promote long-term retention and that these strategies can be executed in WM (Bailey, Dunlosky, & Kane, 2011; Loaiza et al., 2011; Rose et al., 2010). Thus, future research should disentangle the contributions of attentional refreshing and of the nature of encoding strategies to episodic memory. Despite these limitations, our findings provide support for the covert retrieval model (McCabe, 2008) and further suggest that temporal–contextual cues guide episodic recall for items that receive repeated attentional refreshing opportunities.

The data reported also comport with models of WM based on hierarchical levels of activation. For example, we have provided evidence for an attentional refreshing mechanism that retrieves less activated content in order to maintain it, despite other attentionally demanding task goals (e.g., Camos et al., 2009; Cowan, 1999), and manifests predominantly during the encoding phase of tasks that afford attentional refreshing opportunities (McCabe, 2008). Furthermore, data from the present study converge with predictions from the concentric model (Oberauer, 2002, 2005, 2009), such that temporarily and flexibly binding representations to source contexts, particularly temporal contexts, is important during WM encoding. Given that most WM tasks include unrelated items, as well as the evidence that temporal–contextual cues are useful for episodic memory, it may be that an item is more stably bound to a temporal context when it is attentionally refreshed. Indeed, McCabe (2008) demonstrated that delayed recall of items originally studied during a complex span task was greater for earlier serial positions (see also Experiment 3). Thus, the number of attentional refreshing opportunities may have allowed for stronger bindings between earlier presented items and their temporal contexts. The present study elaborates on this finding by showing that the original temporal context can be cued at a delay by providing participants with items from adjacent serial positions within the trial (Experiment 1), as well as through spontaneous access to nearby serial positions after having recalled an item (Experiment 2). Thus, content–context bindings may become more stable and accessible for retrieval from episodic memory with increased opportunities to attentionally refresh that information in WM (McCabe, 2008; Johnson et al., 2002).

Conclusions

The results of the present study suggest that affording attentional refreshing opportunities during WM encoding promotes the use of temporal–contextual cues during episodic memory. Specifically, content–context bindings may become more durable with increasing opportunities to retrieve information back into the focus of attention. The results also suggest that temporal–contextual processing elicited by attentional refreshing during encoding of complex span information can be accessed using externally provided and internally generated temporal–contextual cues during retrieval from episodic memory. While the characteristics that are similar between complex span and supra-span list lengths of simple span remain to be fully elucidated, our data suggest that episodic memory performance relies on temporal associations that are strengthened during encoding of information in WM.

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