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The influence of domain knowledge on the functional capacity of working memory

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ABSTRACT

Theories of expertise have proposed that superior cognitive performance is in part due to increases in the functional capacity of working memory during domain-related tasks. Consistent with this approach Fincher-Kiefer et al. (1988), found that domain knowledge increased scores on baseball-related reading span tasks. The present studies extended those findings using span tasks with independent storage and processing components, and manipulating which component was related to baseball, to determine the source of functional working memory advantages due to domain knowledge. Only when the storage component was related to baseball, and participants were made aware of that relation, did domain knowledge lead to increases in performance on a domain-related span task. The results are discussed in relation to a Long Term Working Memory explanation of expert performance Ericsson and Kintsch (1995), but also show that the relevance of domain knowledge may need to be explicitly recognized to expand the functional capacity of working memory.

Introduction

The acquisition and use of domain-related knowledge is necessary in almost all aspects of our lives. It is a modifiable part of the cognitive system, and a powerful determinant of performance on many different cognitive tasks (for reviews, see Feltovich, Prietula, & Ericsson, 2006; Glaser & Chi, 1988). For instance, researchers have observed that the possession of domain knowledge can improve memory and comprehension of text (e.g. Adams, Bell, & Perfetti, 1995; Hambrick & Engle, 2002; Miller, Stine-Morrow, Kirkorian, & Conroy, 2004; Recht & Leslie, 1988; Schneider, Korkel, & Weinert, 1989; Spilich, Vesonder, Chiesi, & Voss, 1979; Wiley, 2005). Similarly, the possession of domain knowledge generally improves problem solving performance (e.g. Chase & Simon, 1973; Chi, Feltovich, & Glaser, 1981; Gobet & Charness, 2006; Voss, Greene, Post, & Penner, 1983; but see Ricks, Turley-Ames, & Wiley, 2007; Wiley, 1998, for instances in which domain knowledge can have negative effects on problem solving). In a review of the literature on superior cognitive performance due to expertise, Ericsson and Kintsch (1995) concluded that domain knowledge has important effects on the working memory system in the context of domain-related cognitive tasks. In particular, they outline a theory of Long Term Working Memory (LTWM) where access to an organized body of knowledge and easily accessible retrieval structures in long term memory (LTM) expands the functional capacity of working memory while executing domain-related cognitive tasks.

One finding that seems relevant for Ericsson and Kintsch's explanation is the Fincher-Kiefer et al. (1988) result that Baseball Knowledge (BK) specifically led to better performance on a baseball-related reading span task, but had no effect on a neutral reading span task. This is the only study that has directly investigated the effects of domain knowledge using a domain-related measure of working memory capacity (WMC) instead of inferring increases in WMC through improved performance on other tasks. Using the prevailing methodology of the time, Fincher-Kiefer et al. based their baseball-related and neutral span

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assessments on the Daneman and Carpenter (1980) reading span task, in which participants were asked to read sets of sentences and recall the last word from each sentence. Consistent with Daneman and Carpenter's (1980, 1983) theory that reading span tasks are measures of processing efficiency, Fincher-Kiefer et al. interpreted the differences in reading span they observed between the high and low-knowledge participants on the baseball-related span task as being due to differences in processing efficiency. They suggested that increases in the functional capacity of working memory were due to the high knowledge participants' more efficient reading of baseball-related sentences, which left them with more capacity with which to encode and remember the final words (Just & Carpenter, 1992; Just & Varma, 2002).

An alternative explanation for the Fincher-Kiefer et al. (1988) result is that domain knowledge increases the functional capacity of working memory by directly affecting the ability to store and retrieve the to-be-remembered information from the span task. Consistent with the approach of Ericsson and Kintsch (1995), individuals with prior domain-related knowledge may have well-organized, easily accessible retrieval structures in LTM that can expand their functional WMC. According to this view, high knowledge participants would recall more items than low-knowledge participants because they would be better able to use their knowledge to encode and form retrieval structures for the to-be-remembered final words.

Unfortunately, the design of Fincher-Kiefer's et al. (1988) baseball reading span task does not allow for the discrimination between these two alternative explanations: whether increased WMC was due to facilitation in processing of domain-related sentences or storage of domain-related material. Either explanation may be correct, since the span tasks used the same set of domain-related sentences for both processing and storage components (i.e. the memory task was to remember the last word of each sentence that was read). Since the time of this original study, more current versions of the reading span task have been developed in which the to-be-remembered material is independent of the material that is used in the processing component (Engle, Tuholski, Laughlin, & Conway, 1999). In the latest version of the reading span task, a single capital letter is presented at the end of each sentence and these letters serve as the to-be-remembered stimuli (Kane et al., 2004). This change was made because when the same stimuli are used for storage and processing tasks, then reading span scores may reflect reading ability more so than "span" or WMC *per se*. Superior reading ability could lead to an increased ability to generate the final word, based on understanding the gist of the sentence, instead of recalling it from working memory (Engle et al.; Kane et al.). Thus, more recent reading span tasks have used distinct sets of stimuli for the processing and storage components (Conway et al., 2005) to remove as much influence of reading ability from the measurement of the working memory construct as possible.

In the present studies, we likewise update the reading span paradigm used by Fincher-Kiefer et al. (1988) to include independent processing and storage components. Our goal in doing this is to be able to test whether domain knowledge improves the functional capacity of working memory specifically through either the processing or storage components, or even in both ways, by creating complex span tasks where only one of the components contains information that is domain-related.

In Experiment 1, the goal was to replicate the original Fincher-Kiefer et al. (1988) effect. Following the procedure of Fincher-Kiefer et al., participants were given a reading span task and were asked to recall the final word of each sentence for sets of baseball-related and neutral sentences. To foreshadow our results, we found an effect of domain knowledge on baseball-span task performance, but not on neutral span task performance. This set the stage to further test how domain knowledge may have its effect on functional WMC in a series of follow-up experiments that manipulated which one of the span task components (processing or storage) was domain-related.

In Experiment 2, only the processing component of a reading span task was related to baseball. The baseball sentences from Experiment 1 were used as the reading material. The storage component was a neutral letter and participants were asked to recall the letter that appeared after each sentence. Conversely, in Experiment 3, only the storage component of an operation span task was related to baseball. Math equations were used as the independent processing task (operation span tasks are a standard parallel to reading span tasks, Kane et al., 2004) and the to-be-remembered items were the final words of the sentences used in Experiment 1.

If domain knowledge improves the functional capacity of working memory through efficiency or ease of processing, then high knowledge participants should have higher scores on the baseball-related tasks than low-knowledge participants for Experiment 2. If domain knowledge improves functional WMC through facilitating storage and retrieval of to-be-remembered information, then high knowledge participants should have higher scores on baseball-related tasks than low-knowledge participants for Experiment 3. Domain knowledge may of course affect both components of the working memory system. However, it is only through the separate, independent manipulations of these processes that we can begin to discriminate how domain knowledge benefits WMC during the performance of domain-related tasks.

Experiment 1

The goal of the first experiment was to replicate the original Fincher-Kiefer et al. finding (Experiment 2, 1988). In the original study, Fincher-Kiefer et al. found an effect due to possession of domain knowledge on a domain-related span task while controlling for general ability.

Method

Participants

Participants were 80 volunteers from the University of Illinois at Chicago who received course credit as part of an Introductory Psychology subject pool. The sample sizes that were used were based on the anticipated effect size computed from the original results on the baseball-span tasks of Fincher-Kiefer et al. (Experiment 2) which yielded a Cohen's *d* of .857 between high- and low-knowledge groups. With an effect of this size, a sample of $N = 72$ would have had statistical power above .90 for either a two-tailed test between two knowledge groups or a regression analysis using knowledge as a predictor of domain-related performance (estimated by converting Cohen's *d* to R2). In addition, we note that the sample sizes were similar across the studies, and the sample size was sufficient to observe the predicted effects in Experiments 1 and 4b. The participants in all experiments in this paper were recruited and compensated in the same manner, and did not participate in more than one of the experiments.

At the end of the experiment, participants were administered a 45-item Baseball Knowledge (BK) questionnaire. Participants' scores on this questionnaire ranged from 0 to 39 with an average score of $M = 15.49$, $SD = 12.99$ providing a range of knowledge with which to test the main question of interest.

Material and procedures

Participants completed two standard tests of WMC in a separate session. Participants were individually administered both operation span (OSpan) and reading span (RSpan) measures as adapted by Kane et al. (2004) and according to the procedure recommended in Conway et al. (2005). Both measures include a processing task and a storage task on each trial. Participants must complete the processing task while attempting to hold a set of independent stimuli in memory. An example of an OSpan trial is 10/2 + 3 = 2 TWIG, in which participants must verify whether the equation is correct, and then read the final word out loud and attempt to remember it. An example of an RSpan trial is "Andy crossed the yellow heaven. J" in which participants must verify if the sentence makes sense and then read the letter out loud and attempt to remember it. Trials are presented in sets of size 2–5, with three sets of each size. Participants are asked to recall all words or letters at the end of each set. The presentation order of set sizes was randomized. The order of presentation for RSpan and OSpan was also counterbalanced across the range of participants. For each task, a score was computed by averaging the proportion of items recalled in the correct order for each set (following Conway et al.). A WMC composite score was computed by averaging scores for OSpan and RSpan tasks. These composite scores were used to demonstrate that the new neutral and baseball-related span tasks created for these experiments correlated with standard versions of RSpan and OSpan, suggesting that they measured WMC.

The new neutral and baseball-related span tasks based on Fincher-Kiefer et al. (1988) were administered in a separate session than the standard OSpan and RSpan tasks. In the original study, Fincher-Kiefer's et al. procedure differed from current RSpan procedures (as defined by Conway et al., 2005) in five ways. First, half of the sentences were baseball-related. Second, participants recalled the final word of the sentences instead of an arbitrary letter. Third, readers were not asked if sentences made sense, but were asked to remember the full sentences to the best of their ability. Fourth, the length of the sentences varied between 6 and 9 words, instead of the 12–14 in the standard RSpan task. Fifth, set sizes did not vary randomly but rather increased sequentially from 2 to 5 with two trials at each set size. Since this first study is attempting to replicate the findings of Fincher-Kiefer et al. (Experiment 2, 1988), the stimuli and procedures used for the new neutral and baseball-related span tasks followed the original design.

For the current study, the contents of the baseball sentences were derived from fictional commentary used in previous research (Hambrick & Engle, 2002) and real commentary from major league baseball games. Fifty-six pairs of sentences were created ('Appendix A'). For each final to-be-remembered word, we created a baseball-related sentence frame and a neutral sentence frame. As in Fincher-Kiefer et al. (1988) these final words were not baseball-specific jargon (e.g. inning), but rather ambiguous words that could appear in both baseball and neutral contexts (e.g. mound). Each final word appeared on one of two lists of 28 items, so that it would only be presented once to each participant in either the baseball or neutral frame. The two lists were matched for average sentence length (List A, $M = 7.75$, $SD = .79$, words; List B, $M = 7.71$, $SD = .84$, words) and structure as closely as possible. Each participant received one list in the baseball condition and the other in the neutral condition. The presentation order of the baseball and neutral sets was counterbalanced. This created four conditions of to-be-remembered words. Neither order nor list effects were found in any experiment. The complete set of stimuli is included in 'Appendix A'.

Participants were asked to read each sentence aloud. Once they read the last word of the sentence, the researcher advanced to the next sentence. When a series of sentences was completed, participants were asked to recall the last word of each sentence in the set out loud. After attempting to recall the last words from the set, the participants were asked to recall the contents of each of the respective sentences out loud. Finally, participants were administered the same 45-item Baseball Knowledge questionnaire used in Fincher-Kiefer et al. (1988) (this test is originally from Spilich et al., 1979).

Neutral span scores (NSpan) were computed by averaging the proportion correct for each set of neutral trials. Baseball-related span scores (BSpan) were computed by averaging the proportion correct for each set of baseball-related trials.

Reliability of measures

Reliability estimates for the baseball and neutral span tasks were calculated for all experiments as described in Unsworth, Heitz, Schrock, and Engle (2005). In order to compute reliability for the span tasks, the proportion score for the first presentation of every set size (e.g. 2–5) was averaged together to form a sub-score for the baseball and neutral span task. The same procedure was followed for the second presentation of each set size, thus yielding two total sub-scores for the baseball and neutral span tasks. Cronbach's alpha was then computed using these two sub-scores for each span task and were $\alpha = .78$ for the baseball-span task, $\alpha = .50$ for the neutral span task, which suggest that these span tasks are at least moderately reliable. Although the Cronbach alphas are not as high as has been found with other working memory span tasks, this is likely because these reliability scores were computed with only two sub-scores, rather than three.

Importantly, despite the low computed reliabilities, significant correlations were obtained among the span measures as shown in Table 1. Both BSspan and NSspan are correlated with Composite span as well as with each other, which suggests that these span tasks are indeed able to measure the same construct of working memory capacity. Further, one can see there was no relation between BK and NSpan in this sample, $r = .03$, *ns*.

Results

Effects of domain knowledge on span task performance

To test the main question of interest, a regression analysis was performed to investigate whether the degree of BK would predict BSpan task performance after controlling for performance on the NSpan task. A significant effect for BK after variance explained by NSpan performance has been removed would mean that domain knowledge has a facilitative effect specific to performance on the domain-related task (BSpan). In addition, the cross-product for NSpan performance and BK was entered in a second step to evaluate the possibility of an interaction between general ability and domain knowledge. A significant finding for this cross-product term would indicate that the facilitative effect of domain knowledge on domain-related processing *varies* as a function of general ability, as would be the case for example with either compensatory or "rich get richer" effects (Hambrick & Engle, 2002). The compensatory effect is seen when domain knowledge compensates for the lack of working memory on cognitive tasks; whereas, the "rich get richer" effect is observed when high span individuals benefit more from the possession of domain knowledge on domain-related tasks than low span individuals.

As shown in Table 2, both NSpan and BK were both unique predictors of BSpan performance. The cross-product term was not a significant predictor of BSpan performance (change in $R^2 < .003$, $F < 1$) and thus was not retained in the final model. The effect for NSpan means that participants who did better on NSpan generally did better on BSpan.

The critical effect however, was for BK. The significant finding was that BK accounted for unique variance in BSpan performance, after controlling for performance on the NSpan task. This pattern of results is illustrated in Fig. 1. As recommended by Cohen and Cohen (1983), we plotted the predicted values for high and low-knowledge participants using one standard deviation above the mean in BK to serve as the "high" value and one standard deviation below the mean to serve as the "low" value. Note that this figure is for illustrative purposes only, and that in our analyses we did not divide the sample into low and high groups. Rather we treated BK as a continuous variable. (See Aiken and West (1991) for further guidelines on graphing continuous variable interactions.) As shown in Fig. 1, the significant effect for BK was due to low-knowledge participants performing worse on the baseball-related span task than high knowledge participants. This was not due to high knowledge participants having higher WMC in general, because memory performance was similar across knowledge levels for the neutral span task. This means that BK accounted for unique variance in baseball-span task performance, over and above the effects of general ability. Or, said another way, BK was found to specifically relate to better performance on the domain-related span task.

Effects of domain knowledge on processing time

An additional regression analysis was performed to evaluate whether BK affected the processing time for reading sentences on the BSpan task while controlling for processing time on the NSpan task. Predicted reading times are presented in Table 3. (Reading time data was not available for eight participants and one participant was omitted due to having average reading times more than 2 *SD* above the mean). As seen in the second panel in Table 2, the NSpan processing time accounted for a significant amount

Table 1
Pearson correlations for span tasks and Baseball Knowledge scores.

	Bspan	Nspan
Experiment 1		
Bspan	1	
Nspan	.70**	1
Composite span	.49**	.47**
BK	.19	.03
Experiment 2		
Bspan	1	
Nspan	.63**	1
Composite span	.48**	.50**
BK	.12	.17
Experiment 3		
Bspan	1	
Nspan	.60**	1
Composite span	.61**	.57**
BK	.01	−.02
Experiment 4a		
Bspan	1	
Nspan	.63**	1
BK	.10	.08
Experiment 4b		
Bspan	1	
Nspan	.50**	1
BK	.28*	−.02

Note: BK, Baseball Knowledge.
* $p < .05$.
** $p < .01$.

Table 2
Regression analyses for baseball-related span task performance in Experiment 1.

Variable	R^2	F	β	t	sr^2
BSpan scores	.52	41.5**			
NSpan scores			.70	8.80**	.49
BK			.17	2.08*	.05
BSpan processing times	.55	42.14**			
NSpan processing times			.69	8.33**	.50
BK			−.18	−2.17*	.07

Note: R^2, variance accounted for by model; β, standardized regression coefficient; sr^2, squared semipartial correlation; BK, Baseball Knowledge.
* $p < .05$.
** $p < .01$.

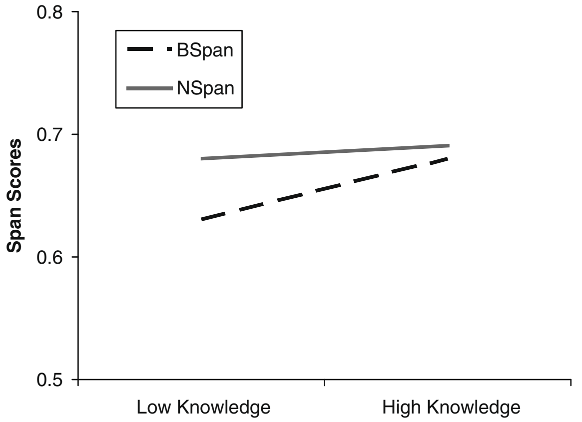

Fig. 1. Predicted values for span scores as a function of span task for ±1 *SD* in domain knowledge in Experiment 1.

Table 3
Predicted values for processing times (ms) on span tasks for ±1 *SD* in domain knowledge in Experiments 1–4.

Variable	BSpan	NSpan
Experiment 1		
High knowledge	3447	3335
Low knowledge	3617	3616
Experiment 2		
High knowledge	5006	5106
Low knowledge	5326	4988
Experiment 3		
High knowledge	6260	6242
Low knowledge	6556	6493
Experiment 4A		
High knowledge	4460	4767
Low knowledge	5778	5849
Experiment 4B		
High knowledge	5670	5637
Low knowledge	6312	6212

of variance in BSpan processing time. Further, as would be expected, BK was a significant predictor of processing time on BSpan, even after processing time on NSpan was taken into account. The cross-product interaction term was not a significant predictor (change in $R^2 < .001$, $F < 1$). Increased BK tended to decrease processing times, specifically on baseball-related sentences.

Conclusions

The finding of a significant effect for domain knowledge on recall performance in a domain-related span task when general ability is controlled for replicates the main finding of Fincher-Kiefer et al. (1988). Establishing a replication of this result was the main goal of this first study and it sets the stage for a set of systematic follow-up experiments that can test for the source of this advantage.

One of the main reasons why baseball and other sports have been used as a topic for studies of expertise is that such knowledge generally does not correlate with general abilities to the same extent as knowledge about academic topics (Hambrick & Engle, 2002; Schneider et al., 1989; Voss, Vesonder, & Spilich, 1980; Wiley, 1998). The finding of no relation between NSpan performance and BK in this study (as shown in Table 1) is important because it suggests this sample is consistent with the conditions in Fincher-Kiefer et al. (1988) where they matched high and low Baseball Knowledge groups on general ability.

However, as an aside, we note that the pattern of the means observed in this study was slightly different than what one might have expected. Although one might have predicted that high Baseball Knowledge participants should have better scores on baseball-related span tasks as compared to neutral span tasks, in this study, the observed effect seemed to be driven more by low-knowledge participants scoring worse on the baseball-span task than on the neutral task. There is a possibility that this divergence in results is due to the different span task scoring methods used by these two studies. Fincher-Kiefer et al. (1988) used an older scoring method in which participants were given a span score based on the largest set size at which they were able to recall all the to-be-remembered stimuli for a given set. To implement this method with our data, span task performance was rescored, high and low BK groups were created via median split on the questionnaire scores, and a repeated measures ANOVA identical to the one performed by Fincher-Kiefer et al. on the new "largest set size" span scores was performed. Using this method, a significant interaction between BK (high, low) and span task (NSpan, BSpan), $F(1, 68) = 10.97$, $MSE = .347$, $p < .01$, $\eta^2 = .14$, was observed, and we were able to replicate the same pattern of results from Fincher-Kiefer et al. in which high knowledge participants performed better on the BSpan than the NSpan tasks (see Fig. 2). This reanalysis provides additional evidence that the current results replicated Fincher-Kiefer et al.'s original finding.

Although the current pattern of results appears more similar to the original pattern when the "largest set size" scoring method was used, we believe the updated scoring method based on the recommendations of Conway et al. (2005) is more informative. It uses a proportional score across trials, and provides more variability in the data which in turn provides more power with which to find real effects. Using the proportional scoring method could be a reason

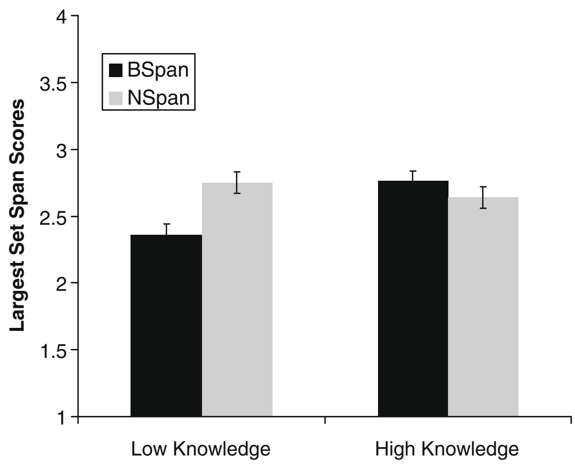

Fig. 2. Mean performance on span tasks (with Standard Error bars) by knowledge group using largest set scoring method for Experiment 1.

that this study was able to demonstrate that low-knowledge participants had particular difficulty on the BSpan task. We suspect that the low-knowledge participants experienced some sort of interference during the baseball-related span task because the sentences were all very similar, whereas high knowledge participants were somehow less susceptible to this interference. We are currently investigating how expertise may protect against interference in immediate memory with another set of studies, and we will return to this point in the general discussion.

Experiment 2

Although the results of Experiment 1 suggest that the possession of domain knowledge led to both faster processing and better memory during a domain-related span task, the design of the particular span task that was used makes the mechanism responsible for better performance unclear. Because the to-be-remembered items were part of the processing task, one cannot determine if better performance was due to the relation of domain knowledge to the processing component (leading to more efficient processing) or due to the relation of domain knowledge to the to-be-remembered information (providing access to well-organized, easily accessible retrieval structures). Thus, the main goal of the next set of experiments was to utilize variants of new baseball-related span tasks to isolate and dissociate the effects of domain knowledge on the processing and storage components of a span task.

In Experiment 2, domain knowledge was related only to the processing component of a new baseball-span task. Based on current reading span tasks, the processing component was a sentence verification task that consisted of either the baseball-related sentences that were used in Experiment 1 or the matched neutral sentences. Importantly, unlike in Experiment 1, the storage component of the span task used in Experiment 2 was an arbitrary letter that followed the sentence (based on Kane et al., 2004), and thus was always unrelated to baseball.

Theoretically, if the processing efficiency explanation of increased functional domain-related WMC is correct, then having more BK should enable individuals to read and verify the baseball-related sentences more quickly, and make fewer errors, than low-knowledge participants. Consistent with the accounts offered by Fincher-Kiefer et al. (1988), Daneman and Carpenter (1980, 1983) and others (Just & Carpenter, 1992; Just & Varma, 2002), this superior processing efficiency should lead to an increase in resources available for the storage component, and domain-related processing efficiency should predict increases in domain-related span task performance. Thus, this experiment tests whether domain knowledge leads to greater processing efficiency during span tasks, which in turn allows for more resources to be devoted to the memory component, thus improving span scores.

Method

Participants

There were 72 participants in this experiment. For all participants in this experiment and the ones that follow, accuracy on the verification task was above the 80% criterion typically used to ensure that participants attend adequately to the processing component of complex span tasks (Conway et al., 2005). Scores on the Baseball Knowledge questionnaire ranged from 0 to 42 with an average score of $M = 17.60$, $SD = 13.88$.

Procedure and new materials

This experiment followed the same procedure as Experiment 1 except for the substitution of new BSpan and NSpan tasks. The new span tasks combined the 56 baseball-related and neutral sentences used in Experiment 1 with neutral letters. As in the standard RSpan task, participants completed a sentence verification task in which they were asked to read each sentence out loud and judge whether or not it made sense. Half of the sentences in each set were nonsensical. One of the words within the sentence was replaced so that it did not make sense (e.g. After the *fruit*, the batter charged the mound). The complete set of new materials is included in 'Appendix B' with replaced words in italics. In addition, set sizes were presented in randomized order.

Administration and scoring for the new span tasks were identical to those for the RSpan task used in Experiment 1. The proportion of letters recalled, averaged across the baseball sentence sets, was used to compute BSpan, and the proportion of letters recalled, averaged across the neutral sentence sets, were used to compute NSpan.

Reliability of measures

Reliability estimates for the baseball and neutral complex span tasks were calculated using procedures described in Experiment 1. A Cronbach's alpha of $\alpha = .69$ was found for the baseball-span task, and $\alpha = .50$ for the neutral span task. Again, despite these relatively low reliabilities, significant correlations were found among the various span measures as shown in Table 1 (12 participants are not included in this analysis due to missing scores). Also as shown in Table 1, there was no significant relation between BK and NSpan in this sample ($r = .12$, *ns*).

Results

Effects of domain knowledge on memory performance

The effect of domain knowledge on memory performance on the BSpan task while controlling for performance on the NSpan task was again investigated using regression. As shown in Table 4, only NSpan was a significant predictor of BSpan performance. Participants that did better on NSpan generally did better on the BSpan. However, BK was not found to specifically predict performance on the domain-related reading span task over the neutral reading span task. The cross-product interaction term was also not a significant predictor (change in $R^2 < .001$, $F < 1$). This pattern of results is illustrated in Fig. 3.

Effects of domain knowledge on the processing task

Regression analyses were also performed to evaluate the direct effect of knowledge on the processing task. For the regression analysis on processing times for the sen-

Table 4
Regression analyses for baseball-related reading span performance in experiment 2.

Variable	R^2	F	β	t	sr^2
BSpan score	.39	22.30**			
NSpan score			.63	6.57**	.38
BK			.01	.11	.00
BSpan processing time	.66	62.88**			
NSpan processing time			.79	10.95**	.64
BK			−.23	−3.19**	.14
BSpan score	.39	14.01**			
NSpan score			.62	6.29**	.37
NSpan processing time			.01	0.05	.00
BSpan processing time			−.03	−0.22	.00
BSpan errors	.46	29.23**			
NSpan errors			.18	2.05	.06
BK			−.64	−7.22**	.44

Note: R^2, variance accounted for by model; β, standardized regression coefficient; sr^2, squared semipartial correlation; BK, Baseball Knowledge.
** $p < .01$.

tences, one participant's data was missing because of a computer error, and two participants were omitted for having average reading times more than 2 *SD*s above the mean. Predicted processing times are presented in Table 3. As shown in the second panel of Table 4, processing time on NSpan accounted for a significant amount of the variance in BSpan processing time. Further, BK was also a significant predictor of BSpan processing time even after controlling for NSpan processing time. The cross-product interaction term was not a significant predictor in this model (change in $R^2 < .001$, $F < 1$). These results demonstrate that domain knowledge did have the intended facilitative effect on the efficiency of processing during the domain-related working memory task and this result can be seen as a manipulation check.

In addition, even though an overall effect of BK was not obtained on memory performance, we still tested an efficiency account of domain-related facilitation in working memory by examining whether faster domain-related processing predicted higher domain-related span scores after performance on a neutral span task was taken into account. As shown in the third panel of Table 4, this model did predict a significant amount of variance, but it was all due to the relation between NSpan and BSpan scores. BSpan processing times were not a significant unique predictor of BSpan scores.

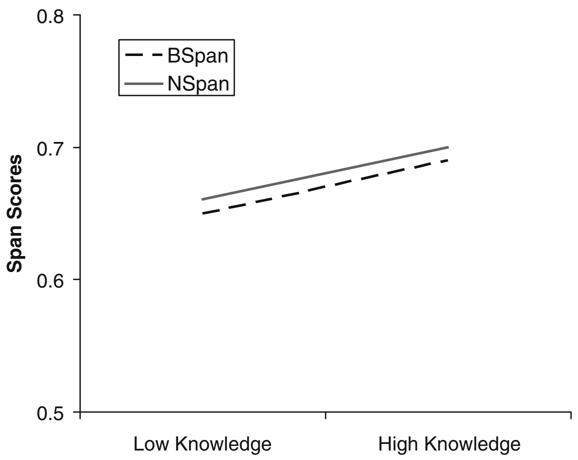

Fig. 3. Predicted values for span scores as a function of span task for ±1 *SD* in domain knowledge in Experiment 2.

Finally, as a second manipulation check, the frequency of verification errors on the baseball-span task over the neutral span task was also examined as a function of BK. As shown in the bottom panel in Table 4, BK was a significant predictor of verification errors on the baseball-related span task, with higher knowledge participants committing fewer processing errors specifically on the BSpan task. This provides converging evidence that the possession of domain knowledge had its intended effect on the processing component and allowed the baseball experts to complete the processing component of the baseball-related task more effectively. Also note that this effect was found even with a restricted range in verification errors, as all participants had at least 80% accuracy.

Conclusions

Although there was evidence that higher knowledge participants were able to process the baseball-related sentences more effectively than lower knowledge participants, efficiency on the processing task did not translate to better memory performance on the baseball-related reading span tasks. Thus, this experiment fails to provide evidence in support of an efficiency of processing explanation for superior functional capacity of domain-related working memory (Daneman & Carpenter, 1980, 1983; Fincher-Kiefer et al., 1988; Just & Carpenter, 1992; Just & Varma, 2002). Based in these results, it does not appear that the relation between domain knowledge and the processing task alone is able to account for the advantages in functional domain-related WMC that have been found in previous studies where both processing and storage tasks were domain-related (i.e. our Experiment 1 and Fincher-Kiefer et al.). Thus, in our next experiment, we manipulated the relevance of domain knowledge to the other main element of span tasks: the storage component.

Experiment 3

The goal for Experiment 3 was to create a parallel set of span tasks where the processing component was unrelated to baseball while allowing the relevance of the storage component to be manipulated. To maintain continuity with Experiment 1 we used the same words as to-be-remembered items for the storage component in this experiment. However, to limit possible interference between the processing task and the storage task, we elected to use an operation span task instead of a reading span task. Thus, for Experiment 3, the processing component of both the BSpan and NSpan tasks consisted of verifying elementary mathematical statements. Thus, this processing component was always unrelated to baseball. On the other hand, the storage component in this experiment consisted of either baseball-related words or matched neutral words. This design enabled us to examine whether differences in high- and low-knowledge participants' performance on baseball-span tasks may be specifically due to advantages in storage (including encoding and retrieval processes) for domain-related information.

Generally, models of skilled memory assert that expert memory excels as a function of the use of well-organized, meaningful knowledge structures in LTM that have been developed over time and though experience with domain-related material (Chase & Simon, 1973; Ericsson & Kintsch, 1995; Simon & Gobet, 2000). In their theory of LTWM, Ericsson and Kintsch have suggested that the benefits of these pre-existing knowledge structures can be extended to include improving WMC. Theoretically, if the LTWM explanation of increased functional domain-related WMC is correct, then BK should predict improved span scores on the baseball-related operation span task. Having more BK should enable individuals to more easily or effectively store or retrieve domain-related to-be-remembered information during the working memory task. In essence, the LTWM theory, along with other expert memory approaches, largely predicts superior functional capacity as a result of the ability to integrate, associate, or elaborate new information with existing knowledge in semantic memory. If such an improvement in performance is indeed found, then other aspects of recall could be examined to provide additional support for this explanation. If intrusions consistent with domain knowledge are found (Arkes & Freedman, 1984; Baird, 2003; Castel, McCabe, Roediger, & Hietman, 2007) or if high knowledge participants are more likely to impose organization or clustering in their recall (Chi & Koeske, 1983; Huet & Marine, 2005; Rawson & Van Overschelde, 2008), these observations would also implicate reliance on prior knowledge structures for the storage component of a domain-related working memory task.

Method

Participants

There were 80 participants in this experiment. Scores on the Baseball Knowledge questionnaire ranged from 0 to 39 with an average score of ($M = 17.15$, $SD = 12.59$).

Procedure and new materials

This experiment followed the same basic procedure as Experiments 1 and 2. For this experiment, two new span tasks were created based on the standard OSpan task (Turner & Engle, 1989). The words for the baseball-related task were the to-be-remembered words from Experiment 1. For the neutral task, a new set of 56 non-baseball-related words were selected to match the Experiment 1 words in written frequency (based on Francis & Kucera, 1982; Neutral $M = 137.55$, $SD = 307.41$; Baseball $M = 133.57$, $SD = 288.59$), number of phonemes (Neutral $M = 4.34$, $SD = 1.35$; Baseball $M = 4.34$, $SD = 1.42$), and word length (Neutral $M = 5.25$, $SD = 1.52$; Baseball $M = 5.25$, $SD = 1.54$).

As in Experiment 1, the 56 items were broken into two 28 item lists, matched for length and frequency. The order of baseball and neutral sets was counterbalanced. This created four versions of the task. The complete set of materials is included in 'Appendix B'. For these new tasks, the administration and scoring was the same as for the standard OSpan task in Experiment 1.

Reliability of measures

Reliability analyses revealed a Cronbach's alpha of $\alpha = .63$ for the baseball-span task, and $\alpha = .50$ for the neutral span task. Again, despite these low reliability estimates, the span measures were significantly correlated, as shown in Table 1 (two participants are not included in this analysis due to missing scores). NSpan was not related to BK, $r = -.04$, *ns*.

Results

Effects of domain knowledge on memory performance

The effect of domain knowledge on memory performance during the baseball-related operation span task was again investigated using regression.

As shown in Table 5, NSpan was a significant predictor of BSpan performance, but BK was not. There was no difference between high and low-knowledge participants in performance on either the neutral or baseball-related operation span tasks. The cross-product interaction term was also not a significant predictor (change in $R^2 < .001$, $F < 1$). Fig. 4 illustrates this pattern of results.

Effects of domain knowledge on processing task

Regression analyses were also performed to evaluate the effects of knowledge on the equation verification times. Here no effect was expected since the processing task was intended to be independent of the domain. Predicted processing times are included in Table 3. Three participants' processing time data were missing due to computer error and three participants were excluded for having average verification times more than 2 *SD* above the mean. As shown in the second panel in Table 5, NSpan processing times accounted for a significant amount of the variance in BSpan processing times, but BK did not. The cross-product interaction term was also not a significant predictor (change in $R^2 < .001$, $F < 1$). This result can be seen as a manipulation check in that performance on the equation verification processing task was unrelated to domain

Table 5
Regression analyses for baseball-related operation span performance in Experiment 3.

Variable	R^2	F	β	t	sr^2
BSpan score	.36	21.32**			
NSpan score			.60	6.52**	.36
BK			.02	.24	.00
BSpan processing time	.74	101.33**			
NSpan processing time			.86	14.13**	.74
BK			.01	.15	.00
BSpan score	.33	11.46**			
NSpan score			.57	5.62**	.31
NSpan processing time			.32	1.64	.04
BSpan processing time			−.25	−1.28	.02

Note: R^2, variance accounted for by model; β, standardized regression coefficient; sr^2, squared semipartial correlation; BK, Baseball Knowledge.
** $p < .01$.

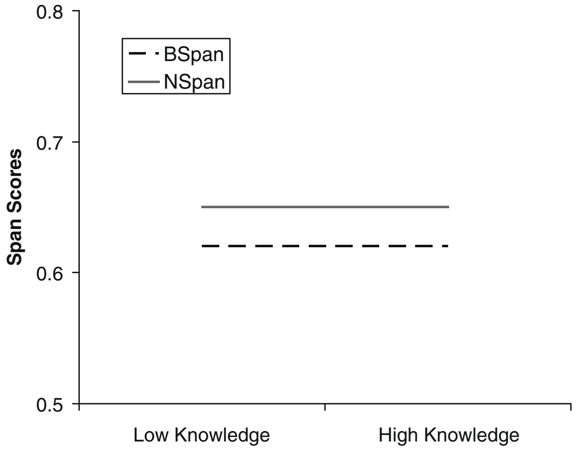

Fig. 4. Predicted values for span scores as a function of span task for ±1 *SD* in domain knowledge in Experiment 3.

knowledge, and the relevance of the storage component also did not affect the relation between BK and verification times.

For completeness, a third model was run to again test the efficiency account, using verification times to predict performance on the BSpan task after controlling for NSpan task performance. As shown in the third panel in Table 5, the model was significant, but NSpan task scores were the only significant predictor of BSpan scores.

A final regression analysis examined errors on the BSpan task, but this model failed to predict a significant amount of variance in verification errors during the baseball-span task ($R^2 = .04$, $F = 1.55$, *ns*).

Conclusions

The lack of a significant effect for domain knowledge on a working memory task when the to-be-remembered items were relevant to that domain of expertise does not support the hypothesis that the functional capacity of working memory improves due to automatic advantages in encoding and storage or retrieval processes. This suggests that the potential domain relevance of to-be-remembered items alone also cannot offer an explanation why Experiment 1 and Fincher-Kiefer et al. (1988) found a facilitative effect for the possession of BK on a baseball-related span task.

One possibility for the null finding in Experiment 3 is that participants failed to activate a baseball-related representation for the to-be-remembered stimuli. Although the words presented in the baseball-related span task were all words that *could* be related to baseball, perhaps the relation of these ambiguous words to baseball was not obvious. In Experiment 1 and the Fincher-Kiefer et al. (1988) study, the to-be-remembered ambiguous words were presented in the context of baseball-related sentences, thus making it more likely that a baseball-related meaning for the words would be activated. Since the to-be-remembered words used for Experiments 1 and 3 were not baseball-exclusive terms, it is possible that the participants in Experiment 3 did not activate the baseball-related meaning for the words. A failure to recognize the baseball theme for the to-be-remembered words could explain why domain knowledge did not impact performance in Experiment 3.

Following this line of reasoning, an interesting question was whether any participants recognized the baseball-related nature of the to-be-remembered words in Experiment 3. To provide some insight on this question, a subset of the participants in this study were asked if they recognized any themes at the very end of the study (as part of debriefing). Of the 32 participants who were asked, 22 were high knowledge and 10 were low knowledge, based on the knowledge split that was used in Experiment 1. For the low-knowledge participants, 60% recognized the baseball theme, while 73% of the high knowledge participants recognized the baseball theme. As can be seen in Fig. 5, when only the data for the "Baseball Aware" participants is considered, the pattern of results looks similar to the interaction pattern found in Experiment 1. This *post hoc* explanation provides some initial evidence that high knowledge participants may need to be explicitly aware that they have relevant prior knowledge in order to improve their working memory performance on domain-related tasks. These findings further imply that the lack of an effect for expertise on the baseball-related operation span task used in Experiment 3 could be attributed to a failure to recognize the relation of the to-be-remembered words to baseball.

Experiment 4

The goal of Experiment 4 was to directly test the hypothesis that participants must be explicitly aware of the relation between stimuli and a domain in order to gain functional advantages of domain knowledge on WMC. Two sub-experiments are performed.

In Experiment 4A, the materials and methodology were identical to those in Experiment 2 except that participants were made explicitly aware of the relation of the verification sentences to baseball. In this task, domain knowledge is relevant for the processing component. If an effect for BK is observed on these span tasks, then this would support

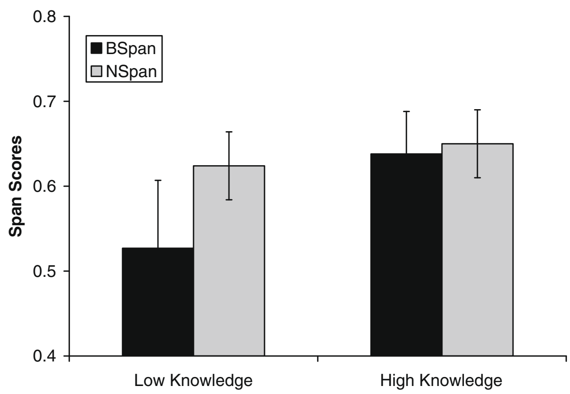

Fig. 5. Mean performance on span tasks (with Standard Error bars) by knowledge group for "Baseball Aware" participants Experiment 3.

the hypothesis that advantages in functional WMC are due to efficiency in processing domain-related stimuli.

In Experiment 4B, the materials and methodology were identical to those in Experiment 3 except that participants were made explicitly aware of the relation of the to-be-remembered words to baseball. Here domain knowledge is relevant for the storage component of the task. If an effect for BK is observed on these span tasks, then this would support the hypothesis that advantages in functional WMC are due to the utilization of domain-related knowledge structures available in LTM that support more effective encoding or retrieval of novel domain-related information.

If either sub-experiment finds an effect, given that Experiments 2 and 3 did not, this would also suggest that participants must be aware of the usefulness of their domain knowledge to expand their WMC for domain-related tasks.

Method

Participants

There were 70 participants in Experiment 4A. Their scores on the Baseball Knowledge questionnaire ranged from 0 to 42 with an average score of $M = 16.12$, $SD = 11.95$. There were 72 participants in Experiment 4B. Their scores ranged from 0 to 41 with an average score of $M = 15.41$, $SD = 12.71$.

Procedure and new instruction

These experiments followed the same procedures for administering BSpan and NSpan tasks as in Experiments 2 and 3. For Experiment 4A, the only difference from Experiment 2 was that participants were explicitly told, "Notice the sentences are related to baseball in this task." For Experiment 4B, the only difference from Experiment 3 was that participants were explicitly told, "Notice that all the words are related to baseball in this task," before the BSpan task.

Reliability of measures

Reliability estimates for the baseball and neutral complex span tasks used in 4A revealed a Cronbach's alpha of $\alpha = .45$ for the baseball-span task and $\alpha = .62$ for the neutral span task, and for tasks in 4B $\alpha = .56$ for the baseball-span task and $\alpha = .43$ for the neutral span task. Despite these low estimates, the span tasks did significantly correlate with each other, as shown in Table 1. Scores on the Baseball Knowledge questionnaire did not correlate with NSpan in either sample (4A: $r = .08$, *ns*; 4B: $r = .02$, *ns*).

Results

Effects of signaled domain relevance of processing task on performance

The pattern of performance on the span tasks for Experiment 4A is shown in Fig. 6. As shown in Table 6, NSpan performance significantly predicted BSpan performance, but BK was not a significant predictor of BSpan performance, nor was the cross-product term (change in $R^2 < .005$, $F < 1$). These results replicate those found in Experiment 2.

Predicted processing times are included in Table 3. (Data was missing for 1 participant due to computer error and 1 additional participant who was removed for having average reading times more than 2 *SD* above the mean). As shown in the second panel in Table 6, both NSpan processing times and BK significantly predicted BSpan processing times. The cross-product term was not a significant predictor (change in $R^2 < .006$, $F = 1.28$, *ns*). These results also replicate those found in Experiment 2.

A regression model testing the efficiency hypothesis again found no significant effect of BSpan processing time on BSpan performance after controlling for NSpan scores and NSpan processing times. As shown in the third panel of Table 6, only NSpan scores significantly predicted BSpan scores.

A final regression analysis presented in Table 6 found that BK was again a significant predictor of errors on the baseball-related reading span task. Participants with more knowledge made particularly fewer errors while verifying the baseball sentences. Again, this result is consistent with Experiment 2 and shows that BK had the intended effect on the ability to engage in the processing component of the baseball-related reading span task, however this efficiency did not translate to better memory performance on the storage component.

Effects of signaled domain relevance of storage task on performance

As shown in Table 7, in Experiment 4B both NSpan and BK were significant predictors of BSpan performance. As shown in Fig. 7, there were no differences between high and low-knowledge participants on NSpan, but critically, high knowledge participants outperformed low-knowledge participants on BSpan. Thus, the replication of the earlier result seen in Fincher-Kiefer et al. and Experiment 1 was again obtained under these circumstances.

Predicted processing times for Experiment 4B are presented in Table 3. (One participant was not included due to average times over 2 *SD* above the mean.) As shown in

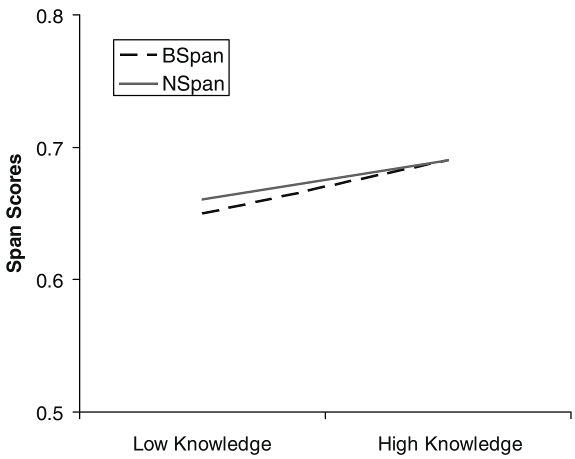

Fig. 6. Predicted values for span scores as a function of span task for ±1 *SD* in domain knowledge in Experiment 4A.

Table 6
Regression analyses for baseball-aware reading span performance in Experiment 4A.

Variable	R^2	F	β	t	sr^2
BSpan score	.40	22.56**			
NSpan score			.63	6.64**	.40
BK			.05	.49	.00
BSpan processing time	.71	78.37**			
NSpan processing time			.68	9.50**	.58
BK			−.30	−4.19**	.21
BSpan scores	.40	14.49**			
NSpan scores			.63	6.29**	.38
NSpan processing time			.08	.50	.00
BSpan processing time			−.14	−.90	.01
BSpan errors	.45	26.82**			
NSpan errors			.16	1.62	.04
BK			−.58	−5.84**	.34

Note: R^2, variance accounted for; β, standardized regression coefficient; sr^2, squared semipartial correlation; BK, Baseball Knowledge.
** $p < .01$.

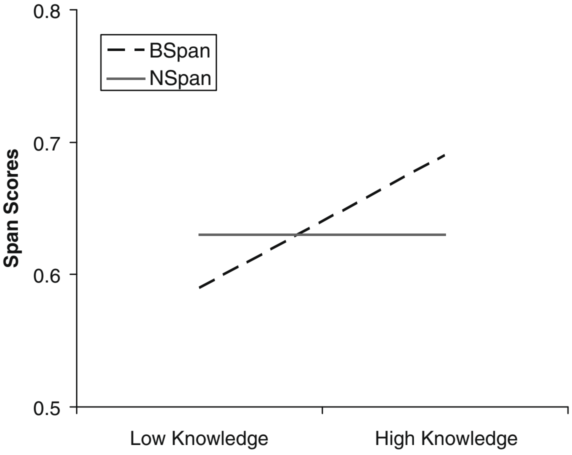

Fig. 7. Predicted values for span scores as a function of span task for ±1 *SD* in domain knowledge in Experiment 4B.

Table 7
Regression analyses for baseball-aware operation span performance in Experiment 4B.

Variable	R^2	F	β	t	sr^2
BSpan score	.32	14.28**			
NSpan score			.51	4.88**	.28
BK			.24	2.29*	.08
BSpan processing time	.76	105.07**			
NSpan processing time			.88	14.18**	.76
BK			.03	.51	.01
BSpan score	.25	7.36**			
NSpan score			.49	4.54**	.24
NSpan processing time			.21	.98	.01
BSpan processing time			−.27	−1.22	.02

Note: R^2, variance accounted for by model; β, standardized regression coefficient; sr^2, squared semipartial correlation; BK, Baseball Knowledge.
* $p < .05$.
** $p < .01$.

Table 7, processing times on NSpan accounted for a significant amount of the variance in BSpan processing times, while BK was not a significant predictor.

Also shown in Table 7, a regression model testing the efficiency hypothesis again found no significant effect of BSpan processing time on BSpan performance after controlling for NSpan scores and NSpan processing times. Only NSpan scores significantly predicted BSpan scores.

The model for predicting BSpan processing errors failed to predict a significant amount of variance ($R^2 = .01$, $F < 1$) and similar to Experiment 3, neither NSpan processing errors nor BK predicted BSpan processing errors.

Additional analyses on the nature of the domain-related memory benefit

In order to provide more evidence for the effect of knowledge on the storage component of this baseball-related OSpan task, we examined a couple of additional memory-related variables. First we examined baseball-related memory intrusions, operationalized as the recall of baseball-related words that had never been presented. These baseball-related intrusions were only found on the baseball-related span task, but other intrusions not related to baseball were also found on this task. A repeated measures ANCOVA on two types of intrusions on the baseball task, with BK entered as a covariate, revealed no main effect for type of intrusion or BK (*F*s < 1). However, as shown in Fig. 8, there was a significant intrusion type by knowledge interaction $F(1, 68) = 7.78$, $MSE = .19$, $p < .01$, $\eta^2 = .10$. The significant interaction was due to the likelihood of intrusions related to baseball increasing with expertise, while the likelihood of intrusions not related to baseball decreased with expertise. These errors in memory performance are informative because they suggest that high knowledge individuals are attempting to use associations within their LTM structures about baseball to remember these storage items, and occasionally some semantically related information gets accidentally retrieved.

However, another memory result was perhaps more surprising. As a second possible way of showing the influence of LTM structures on immediate memory, we exam-

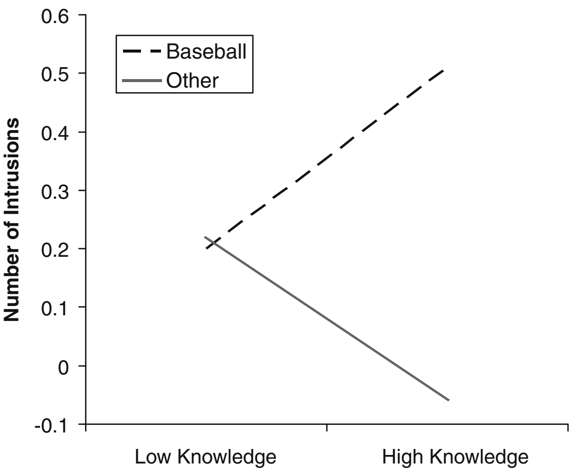

Fig. 8. Predicted values for intrusions on the baseball-span task for ±1 *SD* in domain knowledge in Experiment 4B.

ined if perhaps experts might sometimes impose their own organization on list items (or clustering), even though the instructions were explicitly to recall words in the order they were seen. When the order of recall was examined, it was observed that high knowledge participants were *less* likely to recall presented items out of order than low-knowledge participants on the BSpan. A repeated measures ANCOVA on the number of correct words recalled out of order on the neutral and baseball-span tasks, with BK entered as a covariate, revealed no main effects ($Fs < 1.6$) but a significant span task by knowledge interaction, $F(1, 68) = 4.51$, $MSE = 3.13$, $p < .04$, $\eta^2 = .06$. The pattern of results is shown in Fig. 9. What is notable is that high knowledge participants seem especially able to preserve their order memory in the baseball-related condition. This finding shows that knowledge not only affects the ability to remember a list of domain-related words, but also to maintain the order of that list, which suggests that domain knowledge may also assist in the episodic memory of domain-related stimuli. This result in particular is not clearly predicted by either the LTWM theory or other accounts of skilled memory which discuss advantages in terms of semantic memory. We return to interpretation of this finding in the general discussion.

Conclusions

The findings of Experiment 4 support the hypothesis that domain knowledge improves WMC through advantages in the encoding, storage, or retrieval of the to-be-remembered domain-related information. Critically, Baseball Knowledge was related to performance on a baseball-related span task, but not the neutral span task in Experiment 4B. This result is consistent the LTWM theory of Ericsson and Kintsch (1995) and suggests that better performance on domain-related span tasks is due to the utilization of domain-related memory structures during encoding or retrieval. However, in contrast to Experiment 3, the results of this study demonstrate that this improvement in WMC is dependent upon participants' awareness of the usefulness of their domain knowledge. Further, the findings of Experiment 4A replicated the earlier results of Experiment 2, and show that the lack of effects of domain-related processing on performance was not due to participants being unaware of the baseball material. The disclosure of the baseball-related theme did not have the same effect on the baseball-related RSpan as it did on the baseball-related OSpan. The critical difference between these two tasks is that domain knowledge is relevant for the processing component on the first, but for the storage component on the second.

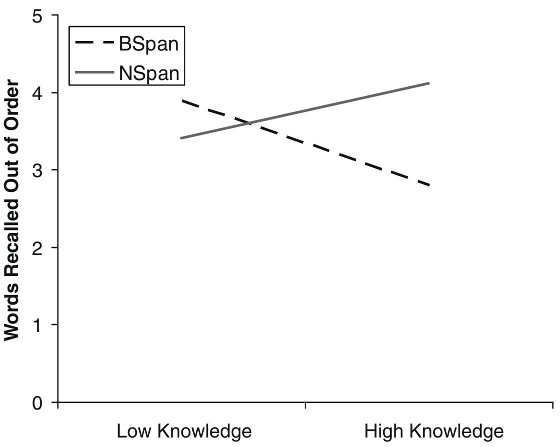

Fig. 9. Predicted values for words recalled in wrong order as a function of span task for ±1 *SD* in domain knowledge in Experiment 4B.

Discussion

The purpose of these studies was to determine how domain knowledge has its effect on the functional capacity of working memory during domain-related tasks. We replicated the Fincher-Kiefer et al. (1988) effect, and attempted to extend those findings using baseball-related span tasks that independently manipulated whether processing or storage components were related to the domain. Somewhat surprisingly, no differences due to BK were found for either of the two complex baseball-related span tasks used in Experiments 2 and 3. Only in Experiment 4, where participants were explicitly informed that the to-be-remembered items were related to baseball, were we able to see an effect of prior knowledge relating to increased functional capacity during a domain-related working memory task.

It is clear that the individual differences in BK were a significant predictor of performance on baseball-related, but not general, working memory span tasks in Experiment 4. Although the correlation between BK and baseball-span scores was only $r = .28$, this correlation is similar in magnitude to correlations between several other individual differences measures and WMC span scores. In adult populations, age has been found to relate to decreases in span scores at about $r = -.17$ (Hambrick & Engle, 2002; Logie & Duff, 2007). Individual differences in reported life stress show similar size correlations with operation span scores ($rs = -.20$ to $-.30$ for comparable set sizes; Klein & Boals, 2001). Other individual differences, particularly gF as measured by the Ravens Advanced Progressive Matrices, tend to show slightly stronger correlations with span scores (*r*s around 35, Kane et al., 2004; Unsworth & Engle, 2005.

What do these improvements in span scores due to possession of domain knowledge represent? Although span tasks are generally used to assess individual differences in the general ability to control one's attention, we do want to make clear that was not the purpose of administering these baseball-related span tasks. These improved span scores do not represent an increase in general attentional capacity, but rather an increase in immediate memory that is specific to performing domain-related tasks when participants have awareness that they possess relevant prior knowledge (*cf* Dunlosky & Kane, 2007; Turley-Ames & Whitfield, 2003).

As a result of the manipulations used here, which isolated the relation of domain knowledge to either the processing or storage components of the working memory task, we were able to determine that increases in functional capacity were only found when it was the storage component of the task that was domain-relevant. The results of two experiments where the processing component was related to domain knowledge showed an effect of prior knowledge on the processing task. However, processing advantages failed to predict improvements in memory performance, and as a result, these studies failed to support an efficiency account.

Instead, this set of experiments demonstrated that the effects of domain knowledge on the functional capacity of working memory depended on the to-be-remembered items being domain-related, and participants being aware that they possessed relevant knowledge structures for the to-be-remembered stimuli. In combination, this allowed high knowledge participants to better remember the domain-related storage items. Therefore, the results of Experiment 4 are most consistent with the explanation of improved functional WMC as being due to differences in the ability to store and retrieve novel task-related information through the use of knowledge structures available in LTM (Ericsson & Kintsch, 1995; Gobet, 2000). Having domain knowledge allows participants to use associative and elaborative memory strategies which would improve performance specifically on the domain-related span tasks (Belleza & Buck, 1988; Cokely, Kelley, & Gilchrist, 2006; Ericsson & Staszewski, 1989; McNamara & Scott, 2001; Turley-Ames & Whitfield, 2003; Van Overschelde & Healy, 2001; Wiley, 2005). The use of existing knowledge structures in semantic memory to support memory for new information is also consistent with the pattern of intrusion errors that was found on the baseball-span task (Arkes & Freedman, 1984; Baird, 2003; Castel et al., 2007).

However, there were two unexpected findings that emerged from this set of studies that do not obviously follow from the LTWM or skilled memory accounts of expert performance. The first was the recognition that what really drove the pattern of results in Experiment 1 was not better performance on the baseball-related span task by the high knowledge participants, as much as poorer performance on the baseball-related span task by baseball novices. Although this pattern was not replicated in Experiment 4, this may have been a function of a key methodological difference in the presentation order of set sizes. Whereas Experiment 1 presented trials in order of increasing set size based on the procedures used originally by Fincher-Kiefer et al. (1988), in Experiments 2–4 we used the more standard randomized order of set size presentation (Conway et al., 2005). There was a good reason for this methodological change in the field. May, Hasher, and Kane (1999) discovered that presenting span tasks using increasing set sizes can lead to lower estimates of span than decreasing or random orders. This effect was seen most acutely with older participants, and has been attributed to a build-up of proactive interference (see also Friedman & Miyake, 2004; Kane & Engle, 2000). Bunting (2006) has also demonstrated the effect of proactive interference on span task performance with an ingenious design that specifically manipulated and released participants from proactive interference during span tasks. Span scores were higher when participants were released from proactive interference by introducing a new type of to-be-remembered stimuli that was not similar to the memoranda that had been used for previous span trials. Based on these findings, we suspect that set size order and the similarity of the stimuli were important factors in producing the pattern of results seen in Experiment 1. The suggestion to be taken from these other studies is that low-knowledge participants may have experienced more proactive interference on this baseball-related span task, which is why they performed worse on the baseball-span task than the neutral span task.

A second unexpected finding was that high knowledge participants exhibited better *order* memory for the items in Experiment 4B. This result diverges from what one might predict if the advantages in memory are due to better integration or more elaborative encoding into semantic knowledge structures in LTM. It also diverges from the results of memory-for-word-list studies that have found that when co-occurrence expectancies are instilled during early word lists, it harms memory for exact word order on later lists (Botvinick & Bylsma, 2005). These co-occurrence associations instilled through practice can be thought of as similar to the associations formed in LTM of experts (Ericsson & Staszewski, 1989; Glaser & Chi, 1988). Other studies have found that semantic relatedness among items on a list improves overall recall, but harms order memory (e.g. Poirier & Saint-Aubin, 1995). Again, these results would have predicted the opposite effect of expertise on order memory especially on a domain-related span task.

Instead, the order memory result suggests that experts may also experience superior or more distinctive episodic traces. Traditionally, although benefits have been found in perceptual memory for meaningful domain-related information, this has been interpreted as being due to expertise allowing experts to encode rapidly presented information on a deeper, semantic level. So in the past, better episodic memory has generally been explained as a function of better semantic processing. Although use of pre-existing knowledge structures in semantic memory may account for a large part of expert memory advantages, there may also be a role for superior veridical memory of episodic context as well. The possibility that episodic representations can support better performance on working memory tasks has just begun to receive attention in the working memory literature, with Baddeley (2003) proposing the addition of an "episodic buffer" to his working memory model, and recent findings of Unsworth and Engle (2006) emphasizing the role of temporal context in retrieval during span tasks. The present results offer some novel evidence that an episodic mechanism may also underlie superior working memory in experts.

The suggestion that domain knowledge may afford better episodic memory is also consistent with the spirit of recent findings which have begun to explore how domain knowledge may enable more distinctive item-specific processing as well. In a study looking at memory for football team names, high knowledge participants were not just better able to recall items on a list, but were especially likely to recall an "oddball" college team presented among a list of pro teams (Van Overschelde, Rawson, Dunlosky, & Hunt, 2005). In another study, examining memory for lists of football terms and names, high knowledge individuals' free recall was greater in conditions that encouraged distinctive processing (i.e. both organizational and item-specific processing) than in conditions that only encouraged organizational processing (Rawson & Van Overschelde, 2008). Additionally, high knowledge individuals showed greater gains than low-knowledge individuals from a pleasantness rating task that encouraged more distinctive processing. These sets of results both suggest that having domain knowledge can allow participants to engage in more distinctive encoding (Rawson & Van Overschelde, 2008; Van Overschelde et al., 2005). Further, it seems plausible that these distinctiveness effects may be related to our other unexpected finding: the experts' ability to resist proactive interference. By being able to make more distinctions among the items, higher knowledge participants would have been less affected by similarity and therefore less prone to proactive interference.

Thus, the results of these studies suggest several possible mechanisms that may underlie the improved functional capacity of experts during domain-related tasks. The findings generally show that it is not the efficiency of processing during domain-related tasks *per se* that is driving better memory performance. Instead, they provide support for approaches that suggest that the functional capacity of working memory can be expanded through the use of relevant, well-organized knowledge structures in LTM. However, LTWM and other accounts of skilled memory seem less able to account for the order memory and proactive interference findings found here. In general, the roles of distinctiveness and episodic traces have received much less attention than the role of integrating new information into existing semantic knowledge structures in explaining expert memory performance (Gobet, 2000; Rawson & Van Overschelde, 2008; Van Overschelde et al., 2005). The present results suggest that this indeed is a direction that needs more exploration to fully explain how expertise supports better memory and cognitive functioning.

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Appendix A

Baseball and neutral span sentences for Experiment 1

After the pitch, the batter charged the mound.
After finals, my laundry was a large mound.

That ball went into the upper deck.
The chairs fit well on the deck.

The pitcher wound up and threw a curve.
The car sped up around the last curve.

Hanson has just come up from the minors.
Cigarettes are illegal to sell to minors.

The pitcher leads the league with 21 wins.
Jane always buys lottery ticket and never wins.

Jay has been known for his quick release.
Jay is going to rent the new release.

That hit should be good for a double.
That special order will cost you double.

Ryan has allowed four hits and one run.
Ryan hopes his car will start and run.

That pitch just brought up a full count.
My nephew Nick just learned how to count.

Tonight there are 18,000 fans in attendance.
Schools are very concerned with attendance.

The pitcher begins his windup and delivers.
The new restaurant is open and delivers.

The runner goes in headfirst and is safe.
The neighborhood is well thought of and safe.

The rain made the umpires delay the game.
The chess masters met for their final game.

It is a pop fly into the stands.
Sitting hurts Joe's back so he often stands.

It is a swing and a miss.
The old building is hard to miss.

The Tigers are ahead in the pennant race.
The election will be a very close race.

Luckily that pitch went off the helmet.
Luckily the skater was wearing a helmet.

That throw was fast, low, and outside.
The weather was sunny and nice outside.

Here's the pitch and swing of the bat.
The people were frightened by the bat.

The third baseman made an amazing stop.
It takes time for a train to stop.

That hit went to the warning track.
That horse ran around the dirt track.

After that call, the manager has left his bench.
After the bus left, John sat on the bench.

Harvey made his way to the plate.
Harvey made a mess on his plate.

The shortstop made a great running catch.
The rainbow trout was a great catch.

Felix stepped into the batter's box.
Felix picked up the cardboard box.

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Appendix A (*continued*)

The runner rounds the bags and slides into home.
The shopper rounded up her bags and went home

The hit is to the right and is foul.
The smell from the back dumpster is foul.

This finally ends the team's losing streak.
The comet crossed the night sky in a streak.

Harvey made his way to the plate.
Harvey made a mess on his plate.

The students learned to compute the class average.
The left-hander has a .310 batting average.

Johnson sat and thought for a second.
Johnson rounds first and goes toward second.

Larsen took a cheap seat in coach.
Larsen takes the sign from the coach.

The movie is excellent but it is checked out.
The shortstop throws and the runner is out.

This could be the best new television series.
This could be the team in the World Series.

This lawyer's success depends upon his courtroom defense.
This team's success depends upon good infield defense.

Sam shut down the store to celebrate the victory.
Sam shut down the Pirates in the victory.

Marshall's driving is hard on the car's clutch.
Marshall is known to hit well in the clutch.

This new music group is marketed to the young.
The pitcher is a contender for the Cy Young.

They were caught kissing behind the bleachers.
That hit is a rocket to the bleachers.

Unfortunately the statue fell off its base.
Unfortunately, three runners were left on base.

Deron loves to take a long Sunday drive.
Deron swings and it is a hard line drive.

Smith thinks his earnings will triple.
Smith reaches third with a triple.

The steak was quite rare inside.
The slider broke to the inside.

Old photos and letters are things people save.
The pitcher will pick up his first save.

The clearance price is on the tag.
The runner slides in under the tag.

By running errands, Bob avoided having to sweep.
By winning today, the bobcats avoided the sweep.

It is a great night for an evening walk.
It looks like this will be an intentional walk.

Sanchez is in his thirties and still single.
Sanchez is safe on first with a single.

The pedestrian tripped and fell on his knees.
The slow pitch broke at the batter's knees.

Steve needs to buy tickets for the play.
Steve needs to watch for the squeeze play.

He leads the union and started the strike.
He throws a high fastball for a strike.

Appendix A (*continued*)

The overpayment of taxes is a common error.
That overthrow of first was a crucial error.

The farmer was standing in his field.
The hit goes deep to center field.

The two angry neighbors need to settle the score.
In the eighth inning, there is still no score.

The Olympic torch is carried to the stadium.
The fans are pouring into the stadium.

The judge was asked to state his controversial position.
The Yankees' shortstop is the best at that position.

The math class is going to learn division.
The victor will be the leader of the division.

Appendix B

Baseball-related OSpan and RSpan materials for Experiments 2–4

Set 1:		
After the **fruit**, the batter charged the mound.	R	
After ***couch***, my laundry was a large mound.	R	
IS (9 ÷ 3) − 2 = 1 Y	MOUND	MOIST
That ball went into the upper deck.	Q	
The ***science*** fit well on the deck.	Q	
IS (4 ÷ 1) − 3 = 1 Y	DECK	BUCK
The ***piano*** wound up and threw a curve.	L	
The car sped up around the last curve.	L	
IS (4 × 1) − 2 = 3 N	CURVE	TREND
Hanson has just come up from the minors.	B	
Cigarettes are illegal to sell to minors.	B	
IS (6 ÷ 3) − 1 = 2 N	MINORS	ROMANS
The pitcher leads the league with 21 wins.	F	
Jane always buys lottery ticket and never wins.	F	
IS (10 ÷ 1) − 6 = 4 Y	WINS	LIDS
Jay has been known for his quick release.	J	
Jay is going to rent the new release.	J	
IS (8 × 2) − 1 = 15 Y	RELEASE	REMARK
That hit should be good for a double.	M	
That special order will cost you double.	M	
IS (3 ÷ 3) + 6 = 6 N	DOUBLE	BATTLE

(*continued on next page*)

Appendix B (*continued*)

Ryan has allowed four hits and ***sad*** run.	F	
Ryan hopes his car will start and run.	F	
IS (10 × 1) − 1 = 10 N	RUN	AGE
That ***wind*** just brought up a full count.	X	
My nephew Nick just learned how to count.	X	
IS (8 ÷ 8) + 1 = 2 Y	COUNT	GRANT
Tonight there are 18,000 fans in attendance.	L	
Schools are very concerned with attendance.	L	
IS (6 ÷ 2) + 5 = 8 Y	ATTENDANCE	APPRENTICE
The pitcher begins his ***dirt*** and delivers.	R	
The new restaurant is open and delivers.	R	
IS (5 × 3) + 2 = 17 Y	DELIVERS	BELIEVERS
The runner goes in ***yesterday*** and is safe.	B	
The neighborhood is well ***back*** of and safe.	B	
IS (4 ÷ 2) − 1 = 1 Y	SAFE	ROOF
The rain made the umpires delay the game.	Q	
The chess ***pickles*** met for their final game	Q	
IS (5 ÷ 2) + 2 = 11 N	GAME	NOTE
It is a pop fly into the stands.	H	
Sitting hurts Joe's back so he often stands.	H	
IS (8 ÷ 1) + 3 = 12 N	STANDS	SEARCH
It is a swing and a miss.	M	
The old building is hard to miss.	M	
IS (9 × 3) − 1 = 26 Y	MISS	TELL
The Tigers are ***library*** in the pennant race.	X	
The election will be a very close race.	X	
IS (7 × 4) + 1 = 30 N	RACE	RISE
Luckily that ***happiness*** went off the helmet.	L	
Luckily the skater was wearing a helmet.	L	
IS (10 × 2) − 3 = 17 Y	HELMET	HOCKEY
That throw was ***purple***, low, and outside.	Q	
The ***leather*** was sunny and nice outside.	Q	
IS (3 × 3) − 2 = 7 Y	OUTSIDE	SURFACE
Here's the pitch and swing of the bat.	H	
The people were frightened by the bat.	H	
IS (8 ÷ 8) + 1 = 1 N	BAT	HAM

Appendix B (*continued*)

The third baseman ***slept*** an amazing stop.	B	
It takes ***smoothie*** for a train to stop.	B	
IS (5 ÷ 1) + 1 = 5 N	STOP	STEP
That hit went to the warning track.	F	
That ***jello*** ran around the dirt track.	F	
IS (4 × 1) + 4 = 8 Y	TRACK	DRUNK
After that call, the ***brick*** has left his bench.	R	
After the ***algebra*** left, John sat on the bench.	R	
IS (9 ÷ 1) − 4 = 4 N	BENCH	LUNCH
Harvey ***typed*** his way to the plate.	J	
Harvey made a mess on his plate.	J	
IS (8 ÷ 1) + 6 = 15 N	PLATE	TRACE
The ***turtle*** made a great running catch.	B	
The rainbow trout was a ***computer*** catch.	B	
IS (5 × 1) + 5 = 9 N	CATCH	BRUSH
Felix stepped into the batter's box.	R	
Felix ***heard*** up the cardboard box.	R	
IS (9 × 2) + 1 = 20 N	BOX	BUY
The runner rounds the bags and slides into home.	Q	
The shopper rounded up her bags and went home	Q	
IS (6 ÷ 2) + 2 = 5 Y	HOME	PART
The hit is to the right and ***eaten*** foul.	X	
The smell from the back dumpster is foul.	X	
IS (9 × 1) + 4 = 12 N	FOUL	LOAF
This finally ends the team's losing streak.	M	
The comet crossed the night sky in a streak.	M	
IS (10 ÷ 1) + 1 = 11 Y	STREAK	THREAD
Set 2:		
The left-hander has a .310 ***ice cream*** average.	L	
The students learned to compute the class average.	L	
IS (8 ÷ 4) − 1 = 1 Y	AVERAGE	SIMILAR
Johnson ***drizzles*** first and goes toward second.	F	
Johnson sat and thought for a second.	F	
IS (6 ÷ 3) − 1 = 1 Y	SECOND	SOCIAL

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Appendix B (*continued*)

Larsen took a ***word*** seat in coach.	B	
Larsen takes the sign ***sled*** from the coach.	B	
IS (3 ÷ 1) + 2 = 4 N	COACH	CHARM
The movie is excellent but it is checked out.	M	
The shortstop throws and the ***igloo*** is out.	M	
IS (3 × 3) − 2 = 7 Y	OUT	WHO
This could be the best new ***banana*** series.	L	
This could be the team in the World Series.	L	
IS (6 ÷ 3) − 1 = 2 N	SERIES	DEGREE
This lawyer's success depends upon his courtroom defense.	F	
This team's ***water*** depends upon good infield defense.	F	
IS (2 × 3) + 3 = 9 Y	DEFENSE	HUNDRED
Sam ***ate*** down the store to celebrate the victory.	H	
Sam shut down the Pirates in the victory.	H	
IS (8 ÷ 1) − 1 = 7 Y	VICTORY	LIBRARY
Marshall's driving is hard on the car's clutch.	J	
Marshall is known to hit well in the clutch.	J	
IS (6 ÷ 2) + 7 = 10 Y	CLUTCH	SCOTCH
This new music group is marketed to the young.	X	
The pitcher is a contender for the CY Young.	X	
IS (8 × 4) + 2 = 33 N	YOUNG	GROUP
They were caught ***grass*** behind the bleachers.	Q	
That ***grass*** is a rocket to the bleachers.	Q	
IS (4 ÷ 1) − 3 = 2 N	BLEACHERS	TURNPIKES
Unfortunately the ***grape*** fell off its base.	R	
Unfortunately, ***parrot*** runners were left on base.	R	
IS (3 × 2) − 1 = 6 N	BASE	WAIT
Deron loves to take a long Sunday drive.	F	
Deron swings and it is a ***frog*** line drive.	F	
IS (4 ÷ 4) + 1 = 2 Y	DRIVE	PRICE
Smith thinks his ***gobble*** will triple.	R	
Smith reaches ***pimples*** with a triple.	R	
IS (8 × 2) − 2 = 14 Y	TRIPLE	SWIVEL
The steak was quite rare inside.	Q	

Appendix B (*continued*)

The slider broke to ***meal*** inside.	Q	
IS (7 ÷ 1) + 2 = 10 N	INSIDE	BEYOND
Old photos and letters are things people save.	X	
The pitcher will pick up his first save.	X	
IS (9 × 4) − 2 = 34 Y	SAVE	FUND
The clearance ***tree*** is on the tag.	L	
The runner slides in under the tag.	L	
IS (9 ÷ 1) − 3 = 5 N	TAG	JUG
By running errands, Bob avoided having to sweep.	H	
By winning today, the bobcats avoided the sweep.	H	
IS (10 × 2) + 4 = 23 N	SWEEP	BRACE
It is a great night for an evening walk.	R	
It looks like this will be an intentional walk.	R	
IS (8 ÷ 4) − 1 = 1 Y	WALK	NEWS
Sanchez is in his thirties and still single.	Q	
Sanchez is safe on first with a single.	Q	
IS (7 × 4) − 5 = 22 N	SINGLE	FIGURE
The ***lamppost*** tripped and fell on his knees.	L	
The slow pitch ***orange*** at the batter's knees.	L	
IS (7 × 1) − 2 = 5 Y	KNEES	SEEDS
Steve needs to ***jump*** tickets for the play.	B	
Steve needs to watch for the squeeze play.	B	
IS (6 ÷ 2) − 1 = 3 N	PLAY	PLAN
He leads the union and ***cloud*** the strike.	F	
He throws a high fastball for a strike.	F	
IS (9 ÷ 3) − 2 = 2 Y	STRIKE	STREAM
The overpayment of taxes is a ***cat*** error.	J	
That overthrow of first was a crucial error.	J	
IS (4 ÷ 1) + 1 = 5 Y	ERROR	BAKER
The ***wind*** was standing in his field.	M	
The hit goes deep to center field.	M	
IS (6 ÷ 6) + 6 = 7 Y	FIELD	DEATH
The two angry neighbors need to settle the score.	X	
In the eighth inning, there is ***black*** no score.	X	

(*continued on next page*)

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Appendix B (*continued*)

IS (9 × 3) − 3 = 25 N	SCORE	DRESS
The Olympic torch is carried to the stadium.	L	
The fans are ***June*** into the stadium.	L	
IS (6 ÷ 2) − 1 = 1 N	STADIUM	HORIZON
The judge was asked to ***lemon*** his controversial position.	H	
The Yankees' shortstop is the ***India*** at that position.	H	
IS (4 ÷ 2) + 1 = 2 N	POSITION	TOGETHER
The math class is going to learn division.	B	
The victor will be the leader of the division.	B	
IS (5 ÷ 5) + 1 = 2 Y	DIVISION	HOSPITAL

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