When does a good working memory counteract proactive interference?

When Does a Good Working Memory Counteract Proactive Interference? Surprising Evidence from a Probe Recognition Task

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Abstract

It is often proposed that individuals with high working memory (WM) overcome proactive interference (PI) from previous trials, saving WM for task-relevant items. We examined this hypothesis in word-list probe recognition. We found no difference in PI related to span. Instead, ex-Gaussian analysis of reaction time (RT) showed speed advantages for high spans specific to short lists (3–4 items) but absent from longer lists (6 or 8 items). We suggest that high-span advantages in RT are based on finesse during easy trials, not on overcoming PI.

Working memory (WM) span, the limited information held in mind concurrently (Baddeley & Hitch, 1974), correlates well with performance on cognitive tasks (e.g., Cowan et al., 2005a; Daneman & Merikle, 1996; Engle et al., 1999) but we don't know why. One popular hypothesis is that individuals with better scores on WM tests are those best able to inhibit potential distractions that otherwise could displace information in WM needed to carry out the task at hand (e.g., Vogel, McCollough, & Machizawa, 2005). This hypothesis has most often been investigated by assessing effects of information relevant on a previous trial that is now irrelevant, i.e., proactive interference (PI), sometimes using accuracy measures and sometimes speed (e.g., Borella, Carretti, & Mammarella, 2006; Bunting, 2006; Conway & Engle, 1994; Hedden & Yoon, 2006; Kane & Engle, 2000; Lustig, Hasher, & Zacks, 2007; Rosen & Engle, 1998).

According to leading approaches, the relation between span and PI effects should occur across the gamut of memory measures. Alternatively, PI effects may be tied to more situation-specific processes (e.g., retrieval processes in recall: Unsworth & Engle, 2007). We investigate the possibility that high-span participants excel at using certain cues that they glean from the stimulus structure to indicate when it is safe to make rapid responses.

We adapted a procedure to investigate the role of PI in probe recognition (Cowan, Johnson, & Saults, 2005b). On each trial the participant saw 3, 4, 6, or 8 words from the same semantic category (e.g., furniture; clothing; body parts). These list lengths ranged from the core capacity that can be remembered without rehearsal (Chen & Cowan, 2009; Cowan, 2001) to just beyond most participants' capacity with rehearsal present (Miller, 1956). Words were shown one at a time, followed by a probe word from the same semantic

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category as the list. The task was to indicate, as quickly and accurately as possible, whether the probe word had appeared in the list, which was true on half the trials. Each trial block included 4 low-PI trials drawn from different semantic categories, 4 filler trials, and 4 high-PI trials drawn from the same semantic category as the fillers. Previous research with this kind of procedure has shown that the amount of PI is much less for smaller set sizes (Halford, Maybery, & Bain, 1988; Oberauer & Vockenberg, 2009) although there can be some PI even at small set sizes (Carroll et al., 2010; Jonides & Nee 2006). We repeated the procedure of Cowan et al. (2005b) with a larger sample size and collected WM span data from several WM tasks on each individual, all of which correlate well with aptitudes (Cowan et al., 2005a). The main question was whether RT parameters would indicate better resistance to PI by high-span participants or an alternative pattern of high-span benefits.

Refinements in the analysis of reaction time (RT) data clarify the role of speed in WM. As RT data typically produce a skewed distribution with a relatively small number of extraordinarily long RTs, they are well-fit by an ex-Gaussian distribution formed by convolving a Gaussian component with an exponential component. The ex-Gaussian distribution includes 3 parameter values, the mean and standard deviation of the Gaussian component, μ and σ, and the mean (which is also the standard deviation) of the exponential component, τ (e.g., Balota & Yap, 2011 Cousineau & Heathcote, 2004). Individual differences in WM are expected to emerge in the tail of the distribution, indexed by τ, with low-span individuals producing more of the especially long RTs than high spans (McVay & Kane, in press; Schmiedek, Oberauer, Wilhelm, Süß, & Wittmann, 2007). The exact psychological interpretation of these individual differences is still a matter of debate (e.g., whether they reflect encoding or decision factors; see Matzke and Wagenmakers, 2009) but the ex-Gaussian distribution is important in allowing the RT distributions of different groups to be compared in detail, a sensitive means to find possible processing differences. The primary question from our ex-Gaussian analysis is whether low spans will have τ values larger than high spans specifically in high-PI situations, or whether a different pattern emerges.

Method

Participants

Undergraduates (n=98, 42 female) participated for course credit.

Apparatus, Stimuli, and Procedure

Each participant was tested individually in a sound-attenuated booth with computer-driven procedures. The tasks included probe recognition to assess PI effects, and then counting, listening, and running memory spans, in that order. The probe recognition task resembled that of Cowan et al. (2005b), and the span tasks were from Cowan et al. (2005a).

Probe recognition task—Words for this task (presented 5 mm high) were obtained from the norms of Battig & Montague (1969), from 45 disparate semantic categories such as metals, reading materials, kitchen utensils, furniture, fruit, types of human dwelling, clothing, and body parts. (Five of these categories were used only for practice trials.) The words were selected to be high in familiarity and to have maximal inter-category semantic similarity and minimal intracategory similarity.

On each trial the participant saw a 1-s fixation cross followed by a list of 3, 4, 6, or 8 words from the same semantic category, presented individually in successive rows of the screen for 1.5 s each. Then a 0.5-s signal (a string of asterisks) was followed by a probe word from the

same semantic category as the list. The task was to indicate by keypress, as quickly as possible without erring, whether the probe word had appeared in the list.

There was a practice block of 12 trials followed by 8 test blocks of 12 trials each. Each trial block included 4 low-PI, 4 filler, and then 4 high-PI trials. Each of these sets of 4 trials included one trial of each list length (randomized within the set). The four low-PI trials in a block had words drawn from different categories. The four filler trials had words all drawn from the same semantic category (different from those used in the low-PI set), with no single word used more than once in that set. Finally, the high-PI trials had words all drawn from the same semantic category as the filler set, with words from the filler trials eligible to appear again in the high-PI trials.[1] After a block of trials, the semantic categories of that block were not used again.

Span tasks—The WM tasks were drawn from Cowan et al. (2005a). In the scoring method that worked best for all three WM measures, we counted the number of items recalled in the correct serial position in each list and averaged this count across trials for each list length. The list length yielding the largest mean for the participant was the one that served as the span measure. The running span measure was treated as comprising a single list length.

Counting span: Each trial included a display with targets (dark blue circles) mixed with distracters (light blue circles and dark blue squares). There were always 3–9 targets, 1–5 circular distracters, and 1–9 square distracters, which varied independently. Several screens were presented and the participant counted the targets in each one and pronounced the sum aloud. Then there was a recall signal along with a 1000-Hz tone, and the participant was to type the series of screen sums. No sum was repeated more than once within a trial (with no repetition until List Length 7). There were 3 trials with 2 screens each, and then the list length increased by 1 screen for the next 3 trials. This procedure repeated with progressively longer lists until the participant made errors on all three trials at a list length.

Listening span: Based on Kail and Hall (1999), spoken sentences were presented through loudspeakers. The task was to determine if each sentence was true or not and respond by answering aloud, and also repeat the list-final word (e.g., *A fox can drive a truck* – "no, truck"). At the end of the list, the same recall cue as in the counting span task was presented and the sentence-final words were to be recalled aloud in the presented order. Three two-sentence practice trials were followed by three trials per list length. Lengths increased as in the counting span task but no participant advanced beyond 7-sentence lists.

Running memory span: Based on Cohen and Heath (1990), from 12 to 21 spoken digits were presented at a rapid rate (4 items/s). There were 2 practice trials followed by 30 test trials, each of which included one trial of every list length. When the list unpredictably ended, the participant was to recall as many digits as possible from the end of the list by typing the sequence of digits in forward order. The serial positions were judged correct or incorrect counting from the end of the list, the score being the number in a row recalled without error.

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[1]In each trial block, due to a programming error, the first high-PI list began with the same series of words as the low-PI list, up to the length of whichever list was shorter (but followed by a different probe). Consequently, we omitted that first high-PI trial of each block in the results reported here, though the statistical results were very similar when that trial was included.

Results

Span Measures

The mean (and SD) for listening span was 2.94 (0.60); for counting span, 4.70 (1.33); and for running span, 3.20 (0.68). We carried out a factor analysis (principal axis factor method) that provided a single-factor result, and used the factor score for each individual as the measure of WM capacity. That factor was significantly correlated with all of the tests: listening span, $r(97)=.84$; counting span, $r(97)=.70$; and running span, $r(97)=.42$, p's $<.001$. Rather than dividing the participants into span groups we used a general linear modeling approach for further analysis, treating WM span as a continuous variable.

RT Scores for Correct Probe Recognition Responses

A histogram of all RT scores for correct responses suggested continuity of the distribution up through 5 SD beyond the mean, and individual-trial scores beyond that cutoff (4980 ms) were excluded from the analysis, as were scores below 200 ms. The RT pattern, shown in Figure 2, is quite similar to what Cowan et al. (2005b) obtained.

Ex-Gaussian analysis—Parameters of RT were calculated using the QMLE package described by Cousineau et al. (2004) and Heathcote, Brown, and Mewhort (2002). In order to have enough trials for an analysis of the parameters of RT according to an Ex-Gaussian function, in most analyses the data were collapsed across the smaller two list lengths (3 and 4) and across the larger two list lengths (6 and 8), and were collapsed across target-present and target-absent trials. The program yields individuals' predicted and obtained values below which .2, .4, .6, and .8 of the data can be found; the average root mean squared difference between the predicted and obtained values across all cut points were consistently small fractions of RT (for short lists with low and high PI and long lists with low and high PI, respectively, 23, 32, 27, and 44 ms; SEM=1, 2, 2, and 3 ms).

A separate analysis was performed on each parameter with the PI level (low, high) and list length (short, long) as discrete factors and span as a continuous factor. All three analyses showed an effect of list length (Table 1). However, the effect of PI did not approach significance for μ or σ. In contrast, the τ parameter showed a robust effect of PI, which was larger for long lists as the interaction term shows. Thus, the effect of increasing list length occurs for all RT parameters, whereas the effect of increasing PI more selectively affects the right tail of the RT distribution, especially for long lists (in free recall cf. Rohrer & Wixted, 1994; Wixted & Rohrer, 1993).

For the first two parameters, no interaction with WM span approached significance. However, for τ, there was one such effect: span significantly interacted with list length (Table 1). The mean value of τ for short lists correlated with span, $r(97)=-.31$, p<.01; higher span produced lower values of τ, indicating that for short lists, high-span individuals produced fewer long RTs than low spans. In contrast, for long lists there was no such correlation, $r(97)=-.02$, n.s. These correlations are depicted by scatter plots in Figure 3.

Even though the significant interaction did not include PI as a factor, could the span x list length interaction draw more from the high-PI condition? No. An examination of the correlation of span with every condition that entered into the analyses yielded only significant correlations between span and τ for short lists with both low PI, $r(98)=-.30$, p<. 01, and high PI, $r(98)=-.22$, p<.05. Of the twelve correlations with WM for the three parameters, all of the other ten were below 0.1. As Table 1 shows, the τ parameter is quite sensitive to PI overall, so the absence of a span effect on PI is all the more striking.

Further properties of the τ parameter are shown in Table 2; none provides an alternative account of the data. Note especially that the correlations between span and τ for long lists remain very small when corrected for attenuation.

Last, we estimated τ separately for 3- and 4-word lists by collapsing across all other variables, and found similar patterns: a 1-unit increase in the WM factor score corresponded to a change in τ of –42 ms (3-word) and –48 ms (4-word). Thus, it suffices to distinguish between 3–4- word lists, for which high-span individuals produced fewer long RTs than low spans in both PI conditions, versus 6–8-word lists, which show no such span differences.

Proportion Correct

As intended, the mean proportion correct was very high, allowing sufficient correct responses for RT analyses The mean(with SD) was, for short lists with low PI, .98(.04); short lists with high PI, .97(.06); long lists with low PI, .91(.07); and long lists with high PI, .86(.11). Importantly, it is clear that the effects of WM span on RT did not result from speed-accuracy tradeoffs, in which case higher-span individuals should have produced less accurate probe recognition responses than low spans. Instead, the correlations between the span factor and proportion correct on probe recognition were all in the positive direction. They were significant for low-PI trials [short lists, r(97)=.30, p<.05; long lists, r(97)=.23, p<.05] but not for high-PI trials [short lists, r(97)=.12; long lists, r(97)=.13], even though performance was closer to ceiling for low-PI trials. The only significant difference between the correlations was between the largest and smallest ones (.30 vs. .12), p<.05 (Meng, Rosenthal, & Rubin, 1992). When we removed 36 participants who were at ceiling (1.0) for either low or high PI, the short-list, low-PI correlation remained significant, r(61)=.27, p<. 05, whereas the other correlations were positive but nonsignificant (r=.21, .07, .07). Last, when we also removed 6 more participants who were bivariate outliers (Mahalanobis, 1936), all the correlations became nonsignificant but still positive, r(55)=.23, .16, .10, and .20 so there was no hint of a speed-accuracy tradeoff.

Discussion

A clear implication from the present results is that performance advantages of high spans did not stem from any specific ability to respond more quickly in the presence of PI (even though the tau parameter of RT was sensitive to PI overall). That finding is broadly consistent with others showing that at most some, but not all, of the differences between high- and low-span individuals is the ability to perform well in the presence of interference (Burgess, Gray, Conway, & Braver, 2011; Emery, Hale, and Myerson, 2008; Friedman & Miyake, 2004; Oberauer, Lange, & Engle, 2004; Salthouse, Siedlecki, & Krueger, 2006; Unsworth, 2010).

Those previous studies, however, have not been able to determine the mechanism for span-related differences in processing. What we add is an interesting and surprising finding with implications for the nature of processing. We show that high-span individuals respond more quickly than low spans to recognition probes for short lists of 3–4 items, but with no span differences for longer lists of 6 or 8 items, for either PI level. This effect emerged in the tau parameter of the ex-Gaussian distribution, reflecting the slow tail of the RT distribution. Note that this result goes directly against what was a clear expectation *a priori*, that high-span individuals would show less PI than low spans, *especially for longer lists*.

One account of our finding is that high spans take advantage of the fact that short lists are within their basic capacity limits (Broadbent, 1975; Cowan, 2001), which could allow quick responding based on probe recollection rather than familiarity of the probe (to avoid errors from PI; see Feredoes & Postle, 2009). This account meshes well with the work on

interference control by Braver et al. (2007) and Burgess et al. (2011), who have suggested that high spans are proactive in limiting the effects of interference (unlike low spans) only when the task makes the manipulation of interference obvious. Our manipulation of PI primarily through semantic similarity rather than word repetition may be less than obvious. However, high spans may find it obvious that short lists pose less of a problem; short lists result in fewer errors and much less PI than long lists do. Therefore, it makes sense that high spans can take advantage of this situation and respond more quickly in the case of short lists, with fewer long responses.

Low spans do not similarly take advantage of list length as a cue, responding with equivalent slowness (higher tau) regardless of the list length, as illustrated in Figure 2. This is striking, given that accuracy on short lists was still high for those in the lower half of WM (.97, vs. .99 for the upper half). We expect that our results will help guide further research on the nature of span differences, in particular whether metamemory is superior in high spans.

Acknowledgments

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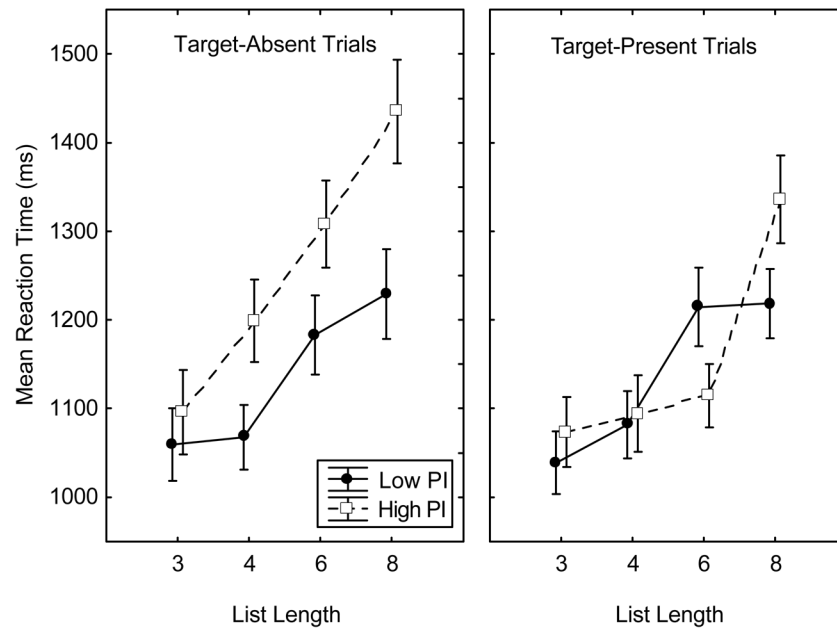
Figure 1.
Mean reaction time (RT) as a function of the list length for low-PI (solid line) and high-PI (dashed line) conditions. Left panel, target-absent trials; right panel, target-present trials. Error bars are standard errors.
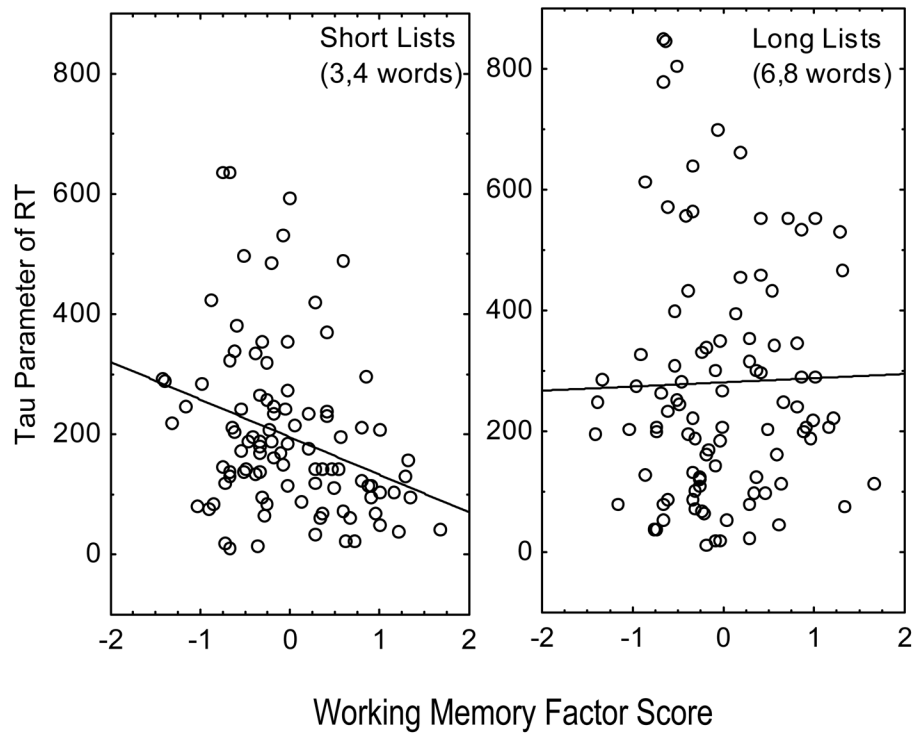
Figure 2.
Scatter plots of each individual's RT tau parameter value as a function of WM factor score. Left panel, short lists of 3 and 4 words; right panel, long lists of 6 and 8 words. The regression line is significantly negative for short lists and nonsignificant for long lists.

Significant Effects in RT Parameters

Parameter	Condition	df	F	p	η_p^2	Mean	SEM
	List Length Effects						
Mu (μ)	3,4 Words	1,96	40.78	.000	.30	876	30
	6,8 Words					965	30
Sigma (σ)	3,4 Words	1,96	12.42	.001	.11	101	10
	6,8 Words					141	11
Tau (τ)	3–4 Words	1,96	18.46	.000	.16	195	14
	6–8 Words					281	21
	PI Effect						
Tau (τ)	Low PI	1,96	11.36	.0001	.11	207	16
	High PI					268	16
	List Length x PI Interaction						
Tau (τ)		1,96	8.49	.004	.08		
	3,4 Words/Low PI					188	16
	3,4 Words/High PI					203	18
	6,8 Words/Low PI					227	24
	6,8 Words/High PI					334	27
	List Length x Working Memory Span Interaction						
Tau (τ)		1,96	5.57	.02	.05	(see Fig. 2)	

Table 1

Table 2

Properties of the Tau Parameter

	Low PI		High PI	
	Short Lists	**Long Lists**	**Short lists**	**Long lists**
Mean (ms)	188	227	203	334
SD	154	234	178	272
Skewness	1.00	1.79	1.39	0.90
Kurtosis	0.89	4.20	2.30	0.98
Reliability[a]	0.84	0.78	0.88	0.71
Raw r	−0.30[*]	0.00	−0.22[*]	0.03
Corrected[b] r	−0.33[*]	0.00	−0.23[*]	0.04

Note. PI=proactive interference. Short lists have 3 or 4 words; long lists have 6 or 8.

[a] The reliability estimate reflects the split-half reliability with the application of the Spearman-Brown formula. Successive data points from each participant in each condition were assigned to the two split halves in alternation. To maintain enough data to carry out Ex-Gaussian analysis on each of these split halves, they were pooled across adjacent pairs of participants.

[b] The tau reliability estimate was used to calculate attenuation-corrected correlations as follows: Corrected r = (Raw r)/(reliability$^{1/2}$).

[*] p<.05.