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Individual differences in the fan effect and working memory capacity☆

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Abstract

In opposition to conceptualizing working memory (WM) in terms of a general capacity, we present four experiments that favor the view that individual differences in WM depend on attentional control. High- and low-WM participants, as assessed by the operation span task, learned unrelated sentences for which the subject and predicate of the sentences shared concepts (fan). Sentences were learned in sets organized by subjects (Experiments 1A and 1B) or predicates (Experiments 2A and 2B). WM predicted accuracy and reaction times on a subsequent speeded verification task, but not learning. In Experiments 1A and 2A, low-WM participants had a steeper, positively sloped fan effect for reaction times to studied items than high-WM participants. In Experiments 1B and 2B, fan was eliminated across but not within memory sets, which eliminated individual differences but not slope to the fan effect. These effects suggest the crux of WM is attentional control, and competition across sets causes individual differences.

Keywords: Attentional control; Fan effect; General capacity; Individual differences; Inhibition; Working memory

Introduction

Rapidly and accurately retrieving familiar information from semantic memory sometimes requires working memory capacity. Cantor and Engle (1993, see Experiment 1 of their report) demonstrated as much when they observed that the magnitude (or slope) of fan effects for retrieval from long-term semantic memory varied as a function of individual differences in working memory capacity. Fan effects occur when the time required to verify a proposition encoded in long-term memory increases concomitantly with the number of propositions collectively committed to memory (Anderson, 1983). Fan effects are the product of interference among shared concepts. The critical result in Cantor and Engle (1993)

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was that participants with less working memory capacity revealed more dramatic fan effects than those with more working memory capacity, and the slopes of individual fan effects statistically accounted for the relationship between working memory capacity and reading comprehension, as measured by the Verbal Scholastic Aptitude Test (VSAT). This result has been used to promote the idea of working memory capacity as amount of activation. According to Cantor and Engle's (1993) theoretical framework, working memory is the activated portion of long-term memory, and working memory capacity is the total amount of activation available for cognition (a similar position was taken in Anderson & Lebiere, 1998; Engle, Cantor, & Carullo, 1992; Lovett, Reder, & Lebiere, 1999). Four experiments are reported here; the results of which are inconsistent with the notion of working memory capacity as amount of activation and inconsistent with Cantor and Engle's (1993) interpretation of individual differences in the fan effect. The current experiments suggest that individual differences in working memory capacity and the fan effect are better explained by a model in which working memory capacity refers to the ability to resist interference rather than a limited amount of activation.

Working memory as capacity

There is some consensus among cognitive psychologists that working memory is a system, or set of processes, that allows for the active maintenance of information in the face of concurrent processing and/or distraction (Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Engle, Kane, & Tuholski, 1999; Miyake & Shah, 1999). Working memory span tasks, including counting span, operation span, and reading span, were developed in accordance with this view of working memory (for examples of each see Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980; Turner & Engle, 1989, respectively). Although different in surface level features, these tasks are structurally similar, for some sort of secondary processing (be it counting shapes, solving mathematical operations, or reading sentences) is imposed during encoding to detract from memory for some memoranda. For example, in the operation span task used in the present set of experiments and described more thoroughly in the Prescreening, participants verify the veracity of simple mathematical equations while attempting to remember strings of unrelated words for later recall. Each trial consists of a mathematical operation followed by a memoranda (e.g., Is $(9 * 2) - 2 = 15$? Road), and recall is cued after sets of 2–5 operation-word strings. Working memory span is the number of words correctly recalled. Assessed as such, working memory capacity reliably and strongly predicts more complex cognitive behaviors such as reasoning, problem solving, and reading comprehension (Engle, 2001).

Working memory span was once commonly described as the capacity to share resources among competing goals (Cantor & Engle, 1993; Daneman & Carpenter, 1980; Just & Carpenter, 1992; Turner & Engle, 1989). Daneman and Carpenter (1980), in the tradition of Baddeley and Hitch's (1974) working memory model, proposed that the processing and storage components of their reading span task made competing demands for a shared resource, and they hypothesized that more efficient processing permits more room for storage. Others, including Turner and Engle (1989), took a similar capacity view of working memory, but they differed from Daneman and Carpenter in the extent to which they conceived of this resource as a domain-specific. Turner and Engle made a convincing argument for the domain-generality of working memory when they demonstrated that operation span, which does not involve reading, accounted for as much variance in multiple measures of reading ability as reading span. Reading span and operation span account for the same variance in reading comprehension, and they load on the same factor in factor-analytic studies (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Kane et al., 1999; Kane et al., 2004). Therefore, the processing component need not be reading in order to predict reading comprehension. According to the "general capacity" model of working memory capacity, working memory is a domain-free memory capacity (Engle et al., 1992). The dual components of operation span, as in other span tasks, require active maintenance (i.e., remembering words for later recall) in the face of concurrent processing (i.e., solving mathematical operations).

Working memory as attentional control

The general capacity model was closely associated with a size metaphor for memory capacity and emphasized the measurement of memory ability, but this model has not held up to empirical investigation (e.g., Conway & Engle, 1994; for a review see Engle, 2001). Engle and colleagues, who were largely responsible for proposing and advancing the general capacity model, have found that pure memorial processes fail to account for the covariation between working memory span and higher-order cognition. They have instead argued that working memory is equivalent to short-term memory plus a general, controlled-attention ability (Engle, 2001; Engle, Tuholski, Laughlin, & Conway, 1999; Kane & Engle, 2003). It is this attentional control component that is responsible for the predictive utility of working memory span tasks. According to Engle and colleagues' "controlled attention" theory of working memory, working memory capacity refers to the attentional ability to maintain activation for goal-relevant information and ignore goal-irrelevant or distracting information via control mechanisms such as goal maintenance and inhibition.

In support of this view, Engle and colleagues have produced a line of correlation-based studies in which were found positive and predictive relationships between working memory capacity and measures of attentional control. This research includes Conway, Cowan, and Bunting's (2001) demonstration that individual differences in working memory capacity are predictive of shadowing errors in a dichotic listening ("cocktail party") paradigm. Kane and Engle (2003) demonstrated a similar relationship but with the Stroop paradigm. The Stroop effect, a quintessential marker of the failure of attentional control, emerges in a color naming task when the to-be-named color appears in the form of a color word and when the ink color and color name do not match (e.g., the word blue written in the color red when the goal is to name the color red). Kane and Engle (2003) showed that those with less working memory capacity are more likely to make Stroop errors than those with more working memory capacity, but only when the Stroop task was composed of mostly congruent trials (e.g., the word blue shown in the color blue). When the task was so biased, those with less working memory capacity could rely on the easier prepotent response of reading the word shown. Adopting this strategy, however, is detrimental to performance on the occasional incongruent trial in which the to-be-named color and color name do not match. Kane and Engle suggested that individual differences in the Stroop effect are evidence of the high span's ability to remain focused on the task goal, which is something that takes attentional control.

Hasher and colleagues also implicate attentional control, specifically the ability to suppress proactive interference, in their view of working memory capacity (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999). Lustig, May, and Hasher (2001; see also May, Hasher, & Kane, 1999) showed that the reading span task is susceptible to the effects of proactive interference (PI). Lustig, May et al. were motivated by the hypothesis that PI builds over many consecutive sets in most any memory span task but especially in the reading span task. Therefore, they manipulated set order, presenting sets either in ascending (smallest to largest) or descending order (largest to smallest), and hypothesized that the descending-order condition would pose less difficulty even for those prone to interference effects, such as older adults in their study. Arguably, the effect of PI should be minimized if the largest (and most difficult) sets are presented first, before the effects of PI have mounted. Not only did this manipulation improve span scores, but the relationship between span and reading comprehension was attenuated. From this perspective, the crux of working memory span tasks is interference, and the ability the control interference from prior episodes is the source of individual differences (Hasher, Tonev, Lustig, & Zacks, 2003; Lustig, Hasher, & Tonev, 2001; Lustig, May et al., 2001; May et al., 1999).

The relevant distinction for us is not between these two theories of attentional control but how the concept of attentional control is an important shift from a focus on memory capacity and the size metaphor for memory. For that reason, we will use the term attentional control to refer collectively to Engle's theory and Hasher's theory, which have more commonalities than differences and which would make identical predictions in our studies. We use the term capacity view to refer to the opposing view of working memory capacity that is focused on quantifying memory capacity.

Working memory and the fan effect

The shift from memorial processes or memory ability to attentional control in contemporary accounts of working memory brought us to reevaluate Cantor and Engle's (1993) experiment with the fan paradigm and their primary explanation of their effect. In Cantor and Engle (1993) and in the basic fan paradigm (Anderson, 1983), participants first learned many "facts" about various people in various locations (e.g., *the artist is in the house*, *the plumber is in the park*, *the teacher is in the boat*). In a subsequent speeded recognition task, they verified the verity of some statements; some were learned target facts and some were unstudied foils (e.g., *the teacher is in the train*). Cantor and Engle's materials were also used in Experiment 1 of this report and are listed in Table 1. In Cantor and Engle, an interference effect was manifest in reaction time to the queried facts; the more facts that were associated with a person or a location, the longer it took participants to verify just one fact about that person or location. In the basic fan paradigm, a fan effect on retrieval can happen for accuracy measures, too. Cantor and Engle (1993) found that the slope of the fan effect for reaction times was greater for those with low working memory capacity than those with high working memory capacity. (Working memory span was assessed with the operation span task, and the low and high groups were those in the lower and upper quartiles of the distribution for operation span, respectively.)

Cantor and Engle (1993) advocated for the general capacity view of working memory and attributed individual differences in the fan effect to differences in the activation capacity of working memory. They argued that working memory is equivalent to the activated portion of semantic long-term memory and that working memory capacity is equivalent to source activation. This view is consistent with other capacity-limited models of spreading activation (e.g., Anderson, 1983). To account for the fan effect, Anderson (1983) suggested that learned facts are stored in networks of semantic-associates. When a test sentence is presented in a fan paradigm like that used by Cantor and Engle (1993), the memory

Table 1
Studied and non-studied Person and Location pairs in Experiments 1A (●) 1B (□)

Location-terms	Person-terms					
	Lawyer	Artist	Plumber	Fireman	Teacher	Doctor
(1) Studied Person and Location pairs						
Boat	● □				●	
Park			● □		●	
Church			● □		●	
Bank			● □		●	
Diner					□	
Hotel					□	
Museum					□	
Airport					□	
House		● □				●
Store				● □		●
Zoo				● □		●
Train				● □		●
Stadium						□
Jail						□
Theater						□
Camper						□
(2) Non-studied Person and Location pairs						
Boat		● □				●
Park				● □		●
Church				● □		●
Bank				● □		●
Diner						□
Hotel						□
Museum						□
Airport						□
House	● □				●	
Store			● □		●	
Zoo			● □		●	
Train			● □		●	
Stadium					□	
Jail					□	
Theater					□	
Camper					□	

Note. Propositions were of the form, *The person is in the location.*

nodes corresponding to the subject and predicate of the sentence are activated, and this activation spreads evenly to related nodes. For example, if given the sentence, *a plumber is in the park*, activation should spread to other locations associated with the person (e.g., *plumber*) and to other people associated with the location (e.g., *park*). Participants correctly verified facts in the recognition test when activation spreading from one node intersected with activation spreading from another node. Because activation spreads equally and evenly to all related nodes, the number of other associative links limits the speed at which activation spreads. Greater source activation, however, speeds the spread of activation. Hence, arguing from Cantor and Engle's vantage, one could attribute faster reaction times and smaller fan effects for those with more working memory capacity to more source activation, or capacity.

An attentional control view of working memory, consistent with Engle's controlled attention view and Hasher's inhibition view, can also account for Cantor and Engle's (1993) effect and an additional prediction that the general capacity view cannot. Individual differences in the fan effect may be due to the ability to avoid making spurious connections (cf. Lustig, Hasher et al., 2001, 2001). Those with low working memory capacity may keep irrelevant propositions unnecessarily active, thereby overloading working memory. The inhibition view was in its infancy at the time the Cantor and Engle paper was published, but Cantor and Engle offered this as an untested hypothesis and challenge to their own interpretation: "If low-span subjects are more vulnerable to interference than are high-span subjects, the fan task could reflect the difference. It remains to be seen whether the differential fan effect observed between high-and low-span subjects in the present studies would be found when the fact-retrieval task involved minimal interference" (p. 1111).

Two kinds of interference are apparent when one considers carefully how participants learned and were later tested on the fan propositions in Cantor and Engle (1993). Cantor and Engle employed a blocked design for the learning procedure. Participants were exposed to the propositions in sets organized by the person-term of the sentences, and the duration of the study time was proportionate to the set size. Referring to the stimuli in Table 1, one can see that the three propositions for plumber (*the plumber is in the park* ... *church* ... *bank*) were studied together and were therefore episodically unique. Although there was interference with the person-term plumber as a result of the fact that it was associated with multiple locations, that interference was limited within a single learning episode. The same was not true for interference from multiple instances of the location-terms. The location-terms were repeated across blocks within the learning procedure. For example, the location-term, park, was shared with two person-terms, plumber and teacher. This particular form of cross-episode interference should be especially difficult for those with low working memory capacity. An attentional control view of working memory would predict that interference from irrelevant episodes is detrimental to low spans but not high spans (Lustig, May et al., 2001).

Our goal was to test the interference hypothesis with the manipulation of response competition between Experiments 1A and 1B. We replicated Cantor and Engle's (1993) design in Experiment 1A and sought one critical effect: a fan size-by-span interaction, which would indicate that the slope of the fan effect for the low-span group was greater than the slope for the high-span group. (*Note*. Cantor and Engle reported the fan effect as a function of *person-fan*, rather than location-fan or total-fan. Because the purpose of Experiment 1A was to replicate Cantor and Engle, the same approach was taken here for all experiments). In Experiment 1B, we eliminated interference from across episodes but not interference within episodes. Location-fan was held at one (i.e., interference or *overlap* among locations in the propositions was eliminated). Person-fan was greater than one to cause a fan effect. According to a capacity-limited view of working memory capacity, individual differences in the fan effect should remain because activation is still divided as person-fan increases and high- and low-span participants differ in the total amount of activation. In contrast and according to attentional control views of working memory capacity, the elimination of overlap among locations (Experiment 1B) should reduce response competition from irrelevant learning episodes and, therefore, eliminate or attenuate individual differences in the fan effect. A main effect of fan was hypothesized in Experiments 1A and 1B.

Participant screening

Participants were screened for working memory capacity on the operation-word span task. Turner and Engle (1989) originally reported this score, and it consistently correlates with performance on tests of cognitive ability (e.g., VSAT and Raven's Progressive Matrices; see Cantor & Engle, 1993; Conway et al., 2002; Daneman & Merikle, 1996; Engle, Kane et al., 1999). Estimates of internal consistency reliability, such as coefficient αs and split-half correlations, are typically in the range of .70–.90 (Conway et al., 2002; Engle, Kane et al., 1999; Kane et al., 2004). Operation span scores are also stable over time (e.g., over a period of three months in Klein & Fiss, 1999).

Participants were tested individually and solved algebraic equations while trying to remember series of unrelated words. A pool of 66 mathematical operations (stated in the form of a question) was randomly paired with an equal number of memoranda (high-frequency, one-syllable, and semantically unrelated words; e.g., Is $(8 * 3) - 3 = 21$? CALF). The stimuli were previously reported in LaPointe and Engle (1990). Each operation began with multiplication or division of two integers, and a third integer was either added to or subtracted from the result. A solution, which was correct half of the time, was provided for each equation. Participants read each operation aloud, said "yes" or "no" to verify its veracity, and read a word. The experimenter initiated presentation of each operation-word string by key press and advanced to the stimuli immediately after the participant read the word. Three question marks followed each set, which had 2–6 memoranda, and cued participants to recall and write the words in serial order on a response sheet. The response sheet contained an equal number of blanks for each trial. Participants were neither told how many words to expect on an upcoming trial, nor were they reminded how many words occurred on a previous trial. However, guessing was encouraged, and recall was not timed.

Three series of each set size (for a total of 15 sets) were presented in a random order that was the same for all participants. Three additional series of two items each were practice. Each participant's working memory span was the sum of the correctly recalled words for trials that were recalled in the correct order and without error (maximum score was 60). Accuracy at solving the mathematical operations was monitored but was not taken into account in the calculation of working memory span. However, participants below 85% mathematical accuracy were excluded. A large number of participants were prescreened on the operation span task for use in these experiments and other research in our laboratory. Only those in the upper or lower quartiles were eligible for these experiments. Experiments 1A and 1B were conducted in one semester, and quartile boundaries were determined by operation span scores from 340 participants. Quartiles for Experiments 2A and 2B were determined by operation span scores from 400 participants. In both cases, the cutoff score for the lower quartile was 10, and upper quartile scores began at 19. Participants were undergraduates from the subject pool of the Psychology Department at the University of Illinois at Chicago and received course credit in exchange for participating in the screening or any of the reported experiments. Participants had English as a first language, normal or corrected-to-normal vision, and normal use of the dominant hand to make rapid keyboard and written responses.

Experiment 1A: Interference from location-terms, a replication of Cantor and Engle (1993)

Method

Participants

Forty-two participants (23 high-span and 19 low-span; $M(SD)_{\text{span scores}} = 23.61$ (5.14) and 6.79 (2.12), respectively) were selected from a pool of 340 participants prescreened on operation span. Eight additional participants (2 high-span and 6 low-span) were excluded for not achieving 63% accuracy on the recognition component of the fan task. There were 8, 24, and 32 verification trials per level of fan, respectively, so participants could miss 3 responses at Fan 1, 9 responses at Fan 3, and 12 responses at Fan 4.

Materials and procedure

The materials and procedure for the fan task (acquisition and recognition) came from Cantor and Engle (1993). The tasks were computerized and the experimental session lasted 30–45 min. In this and each subsequent experiment, the time between the Prescreening and the fan task was different for each participant, but most participants completed both tasks within a week and all participants completed both tasks within a six week period.

Acquisition and retention task. Participants learned 16 sentences of the form, *the person is in the location*. See Table 1 for the materials. Each location-term was associated with two person-terms, and each person-term was associated with one, three, or four location-terms. Hence, person-fan was 1, 3, or 4, and location-fan was 2. Sentences were grouped by the person term (e.g., all sentences for plumber were presented together). The algorithm n(10 s) + 10 s, where n equals the number of sentences to be displayed, determined the presentation duration per group. Oral recall was tested after each set was presented once (presentation of a person-term with a question mark cued recall). A set of propositions was scored as correct if all of the appropriate sentences were recalled in any order and without the generation of any additional incorrect sentences. The experimenter monitored recall and indicated by key press whether a set was recalled correctly or not. This memorization-recall procedure was repeated until a set was correctly recalled on three consecutive cycles. When this criterion was met, each was presented once more. The number of memorization-test cycles per fan set was recorded for data analysis.

Recognition task. The speeded recognition test had four blocks of 32 trials each (16 studied and 16 non-studied). Non-studied (foil) sentences were generated by switching person-terms between sets of studied sentences so that they still reflected the same fan size. Participants verified the veracity of each sentence by key press (keys "1" and "3" represented "yes" and "no," respectively). Reaction time and errors were recorded for data analysis.

Results

Data were analyzed from the acquisition and recognition tasks. The dependent measure for the acquisition task was the number of memorization-recall cycles required to reach criterion. The dependent measures for the recognition task were reaction time and accuracy. The independent measures for both were working memory capacity (i.e., span, high, and low) and propositional fan size (fan: 1, 3, and 4). Trial type (studied and non-studied sentences) was an additional independent measure in the recognition task.

Acquisition and retention task

The low-span group did not require more memorization-test cycles than the high-span group to meet the acquisition criterion. The mean number of memorization-recall cycles (see Table 2) for each level of span was submitted to a fan × span mixed-design analysis of variance (ANOVA). There was a significant main effect of fan, $F(2, 80) = 12.42$, $MSE = 0.25$, $p < .001$. Orthogonal pairwise comparisons showed that fewer memorization-recall cycles were required on average to reach criterion at Fan 1 ($M = 3.12$) than at Fan 3 ($M = 3.51$) or Fan 4 ($M = 3.63$). The difference between Fan 3 and Fan 4 was not significant. (Note: alpha was adjusted downwards by means of the Bonferroni correction for multiple analyses). There was neither a main effect of span nor an interaction between fan and span, $F(1, 40) < 1.0$, $MSE = 0.55$, ns, and $F(2, 80) = 1.51$, $MSE = 0.25$, ns, respectively.

Recognition task

Reaction time. In this and all experiments, reaction times are for correct responses, and reaction times on incorrect response were omitted from data analysis.

Table 2
Means (and *SD*) for the number of memorization-test cycles as a function of fan size and span group for all experiments

Span group	Fan size		
	1	3	4
Experiment 1A			
High-span	3.13 (.43)	3.37 (.51)	3.63 (.61)
Low-span	3.11 (.21)	3.68 (.84)	3.63 (.76)
M	3.12 (.35)	3.51 (.69)	3.63 (.67)
Experiment 1B			
High-span	3.11 (.26)	3.41 (.80)	3.61 (.87)
Low-span	3.27 (.59)	3.79 (.72)	3.89 (.53)
M	3.19 (.46)	3.60 (.77)	3.75 (.73)
	1	2	3
Experiment 2A			
High-span	3.05 (.15)	3.27 (.48)	3.48 (.66)
Low-span	3.12 (.27)	3.38 (.52)	3.38 (.57)
M	3.08 (.22)	3.33 (.50)	3.43 (.61)
Experiment 2B			
High-span	3.05 (.15)	3.36 (.58)	3.52 (.61)
Low-span	3.22 (.33)	3.39 (.45)	3.74 (.64)
M	3.13 (.27)	3.38 (.51)	3.63 (.63)

Note. Perfect recall would result in three memorization-test cycles.

Reaction times greater than 3.0 SDs from each participant's mean were replaced by the value at 3.0 SD. This adjustment affected less than 1.0% of scores in this and each remaining experiment.

We tested the three-way interaction among fan, span, and trial type, but based on Cantor and Engle (1993), we did not expect that the fan × span interaction would vary by trial type. Therefore, mean reaction times (in milliseconds; see Table 3) were submitted to a fan × span × trial type mixed-design ANOVA. As predicted and as found in Cantor and Engle (1993), there was an interaction between fan and span, $F(2, 80) = 3.30$, $MSE = 146{,}983$, $p < .04$. Based on Keppel's (1991) formula for repeated measures, the effect size (ω^2) was .09, which is a medium

Table 3
Means (and *SD*) for correct response times and error rates to studied and non-studied items on the recognition test of Experiments 1A and 1B for high- and low-span participants

Probe type	Response times (in ms)			Mean errors		
	Fan 1	Fan 3	Fan 4	Fan 1	Fan 3	Fan 4
Experiment 1A						
High span						
Studied	1437 (268)	1791 (389)	1809 (375)	.04 (.21)	.74 (1.01)	1.57 (1.41)
Non-studied	1737 (447)	2011 (460)	1998 (372)	.39 (.50)	1.22 (1.35)	1.17 (1.15)
M	1587 (328)	1901 (406)	1903 (359)	.22 (.29)	.98 (.94)	1.37 (.91)
Low span						
Studied	1545 (355)	2144 (671)	2216 (734)	.11 (.46)	1.63 (1.64)	3.16 (2.22)
Non-studied	1985 (401)	2503 (511)	2509 (576)	.63 (.90)	2.63 (1.98)	3.16 (2.79)
M	1765 (329)	2324 (560)	2362 (633)	.37 (.52)	2.13 (1.41)	3.16 (1.71)
Experiment 1B						
High span						
Studied	1407 (509)	1761 (515)	1814 (430)	.32 (.72)	.91 (.97)	1.36 (1.22)
Non-studied	1719 (455)	1896 (456)	1901 (439)	.45 (.67)	1.32 (2.01)	.91 (1.38)
M	1563 (454)	1828 (468)	1857 (396)	.39 (.49)	1.11 (1.05)	1.14 (.88)
Low span						
Studied	1379 (358)	1819 (476)	1938 (363)	.09 (.29)	1.00 (1.11)	1.41 (1.71)
Non-studied	1758 (463)	1923 (371)	1902 (330)	.73 (.88)	1.82 (2.34)	1.32 (1.73)
M	1568 (383)	1871 (409)	1920 (305)	.41 (.53)	1.41 (1.53)	1.36 (1.57)

to large effect (Cohen, 1977). A follow-up test to this interaction confirmed that the slope of the fan effect for reaction time was greater for low-spans ($M = 211$, $SE = 40$) than high-spans ($M = 113$, $SE = 24$), $t(df = 40) = 2.17$, $p < .036$.[1] This comparison of slopes for high- and low-spans is in keeping with our primary hypothesis that high- and low-spans would differ in the magnitude (or slope) of their fan effects. Cantor and Engle showed that the fan effect slope accounted for the relationship between working memory and verbal abilities (as assessed by the verbal scholastics aptitude test, VSAT) and argued that the magnitude of the fan effect appears to reflect the same mechanism as the working memory spans. The pattern of the fan × span interaction was similar for both targets and foils, and thus the test of the full three-way interaction was not significant, $F(2, 80) < 1.0$, $MSE = 42{,}796$, ns. In the absence of any indication that the results are different for targets and foils, we did not analyze these items separately. Additional analyses are reported in Appendix A.

Error rate. Mean errors during verification (see Table 3) were submitted to an analysis like that for the reaction time data. A significant interaction between fan and span indicated that the slope of the fan effect of errors was greater for low- than high-span participants, $F(2, 80) = 8.50$, $MSE = 1.67$, $p < .001$. The effect size (ω^2) was .26, a large effect (Cohen, 1977). A follow-up test to this interaction confirmed that the slope of the fan effect for errors was greater for low-spans ($M = 1.39$, $SE = .11$) than high-spans ($M = .38$, $SE = .06$), $t(df = 40) = 4.52$, $p < .001$. We did not analyze targets and foils separately because the pattern of the fan effect was similar for both, as indicated by the fact that the three-way interaction of fan × span × trial type was not statistically significant, $F(2, 80) < 1.0$, $MSE = 1.92$, ns. Additional analyses are reported in Appendix A.

Discussion

The low- and high-span groups acquired the materials in an equal amount of time, but important individual differences emerged in the recognition task. The low- and high-span groups revealed fan effects for reaction times and errors with the increasing number of propositions associated with the person-terms of the sentences, but the slopes of the fan effects were larger for the low-span group. These results are similar to those of Cantor and Engle (1993, see Experiment 1 of their report). Cantor and Engle reported that individual differences in working memory capacity predicted the fan effect for reaction times, but they did not find additional differences in the fan effect for errors.

It should be noted that the studied propositions in Cantor and Engle's (1993) experiment were atypical in one respect. In their experiment and the current Experiment 1A, the propositions at Fan 1 and Fan 3 were nested subsets of the Fan 4 propositions. For example, as seen in Table 1, the locations for lawyer and plumber together completely overlap with the locations for teacher. In other versions of the fan paradigm (e.g., Anderson, 1983), there is overlap in the items from different fans, but these overlaps do not result in complete subset relationships. Such subset relationships could affect the way in which Fan 4 propositions were represented in memory. In particular, any probe involving a Fan 4 person could be answered by reference to the corresponding Fan 1 and 3 items (e.g., using the above example, any probe involving teacher could be answered by retrieving the locations associated with lawyer and plumber instead of retrieving the teacher locations directly). This implies that the participants need not store four locations with the Fan 4 person-terms at all; rather, they need only store the two related person terms (and rely on the location-fans from there). Thus, the representation that participants may be constructing essentially turns the Fan 4 items into Fan 2 items. The materials in the remaining experiments were constructed to avoid such subset relationships.

The results of Experiment 1A are consistent with the view of working memory capacity as amount of activation, but susceptibility to response competition from the overlap among fan materials, specifically location-terms, may account for the individual differences observed here. In Experiment 1A, location-fan was held constant at two while person-fan varied from one, three, and four. In Experiment 1B, each person-term was associated with a unique location (i.e., location-fan = 1). Two alternative outcomes were foreseen. First, according to a capacity-limited perspective (Cantor & Engle, 1993), the span effects should remain because person-fan has not changed. That is, one would predict that more working memory capacity should permit faster spreading activation to the multiple location-terms associated with the person-terms at Fan 3 and Fan 4. An alternative outcome is that eliminating this specific form of interference (overlapping location-terms) will at least attenuate, if not eliminate, any effect of span. An attentional control view of working memory would make this prediction based on research suggesting that low spans are prone to interference from irrelevant episodes and spurious connections (Kane & Engle, 2003; Lustig, May et al., 2001).

Reports from the participants also lead us to expect the second outcome. Many participants reported that

[1] By slope, we mean the slope of the linear regression line through the data points at each fan level, which takes into account the fact that the distance between Fan 1 and Fan 3 is greater than the distance between Fan 3 and Fan 4.

they used mnemonics to help them learn the fan propositions. For example, some reported trying to remember just the first letter of each location associated with a person-term. So, "plumber PCB" might have helped a participant to remember that the plumber was in the park, church, and bank. Based on attentional control theories of working memory capacity, we would not expect high- and low-span participants to differ in integration and mnemonic strategies such as this (cf. Engle et al., 1992). But, we would expect them to differ in their susceptibility to interference from competing responses that do not fit their mnemonic chunk.

Experiment 1B: No interference from location-terms

Method

Participants

Forty-four new participants (22 high-span and 22 low-span; $M(SD)_{\text{span scores}} = 24.91$ (6.15) and 6.77 (2.56), respectively) were selected from the same pool of participants who completed operation span for Experiment 1A. Two additional participants (1 high-span and 1 low-span) were excluded from analyses for not achieving 63% accuracy on the recognition task.

Materials and procedure

The materials and procedure were unchanged from Experiment 1A, with the exception that there was no overlap among location-terms (location-fan = 1). Studied and non-studied person- and location-terms are shown in Table 1.

Results

The independent and dependent variables were the same as those for Experiment 1A.

Acquisition and retention task

As in Experiment 1A, the low-span group did not require more memorization-test cycles than the high-span group to meet the acquisition criterion. The mean number of memorization-recall cycles (see Table 2) for each level of span was submitted to a fan × span mixed-design ANOVA. There was a fan effect, $F(2,84) = 17.19$, $MSE = .213$, $p < .001$. Orthogonal pairwise comparisons showed that Fan 1 ($M = 3.19$) propositions were acquired faster than Fan 3 ($M = 3.60$) or Fan 4 ($M = 3.75$) propositions. The difference between Fan 3 and Fan 4 was not statistically significant. (Note: alpha was adjusted downwards by means of the Bonferroni correction for multiple analyses). There was neither a main effect of span nor an interaction between fan and span, $F(1,42) = 2.79$, $MSE = .88$, ns, and $F(2,84) < 1.0$, $MSE = .22$, ns, respectively.

Recognition Task

Reaction time. Mean reaction times for correct responses (see Table 3) were submitted to a fan × span × trial type mixed-design ANOVA. Individual differences in working memory capacity were unrelated to the slope of the fan effect for reaction times. Neither the test of the full three-way interaction nor the interaction between fan and span were significant, $F(2,84) = 1.02$, $MSE = 49{,}226$, ns, and $F(2,84) < 1.0$, $MSE = 66{,}794$, ns, respectively. The effect size for the fan × span interaction (which was the critical effect in Experiment 1A) was .01, and the power (by charts from Pearson & Hartley, 1972) was .88 to detect an effect size (ω^2) of .09, or the effect size in Experiment 1A. Therefore, we cannot attribute the failure to detect the critical effect to a lack of power. However, there was a fan effect for reaction times, and the slope of the fan effect was significantly greater than zero, $F(2,84) = 40.96$, $MSE = 66{,}794$, $p < .001$. Additional analyses are reported in Appendix B.

Error rate. Mean errors (see Table 3) were submitted to a fan × span × trial type mixed-design ANOVA. As for the reaction time analysis, individual differences in working memory capacity were unrelated to the fan effect slope for errors. Neither the test of the full three-way interaction nor the interaction between fan and span were significant, $F(2,84) < 1.0$, $MSE = 1.49$, ns, and $F(2,84) < 1.0$, $MSE = 1.83$, ns. The effect size for the fan × span interaction was .01, and the power (by charts from Pearson & Hartley, 1972) was greater than .98 to detect an effect size (ω^2) of .26, or the effect size in Experiment 1A. As in the case of the analysis of reaction times, we cannot attribute the failure to detect the critical effect to a lack of power. There was a significant, positively sloped fan effect for errors, $F(2,84) = 11.81$, $MSE = 1.83$, $p < .001$. Additional analyses are reported in Appendix B.

Discussion

The outcome of this experiment was consistent with our predictions about working memory capacity and attentional control. The high- and low-span groups revealed nearly identical fan effects for reaction times and errors with increasing person-fan, but the absence of location-based interference eliminated the relationship between individual differences in working memory and fan. That is, the low-span group performed like the high-span group when the materials did not contain overlapping location-terms.

The fact that there is still a main effect of fan should come as no surprise. Radvansky, Spieler, and Zacks (1993, see also Radvanksy, 1999) demonstrated that fan effects can be attenuated and even eliminated when the materials can be organized into real world situations, or situation models. In Radvansky et al. (1993, Experiment 1), participants did not show fan effects for reaction times or errors when multiple inanimate objects were represented in a single location (i.e., a single situation model), but they showed fan effects when multiple objects were in multiple locations (i.e., multiple situation models). However, the same was not true when Radvansky et al. used person-terms in place of inanimate objects (see their Experiment 3). In this case, Radvansky et al. showed that facts about people being in locations do not readily give rise to person-based or location-based organization, and in fact participants did not spontaneously use situation models to represent people in general locations. Our current experiment is not a direct replication of Radvansky et al. (1993, Experiment 3), but our person- and location-terms are similar, as are our results. Participants in our study were asked to represent a single person in multiple locations. This not only does not conform to a real-world situation or an easily conceivable situation model, but our materials were not suggestive of one type of situation over another.

Power analyses offered reassurance that we had sufficient power to detect effects of the same magnitude as the critical effects in Experiment 1A. Nonetheless, our conclusions for Experiment 1B are contingent upon further analysis of the between-experiments effect of interference. What we really need to know is whether the differences in slope between high- and low-span participants changes depending on the interference condition. If an attentional control account of working memory is correct, then we should expect to see a difference in the performance for low-span, but not high-span participants between experiments.

Experiments 1A and 1B: Between-experiments analyses

The critical effect in Experiment 1A—the fan × span interaction—was the same for targets and foils, and therefore we collapsed across the trial type variable in the between-experiments analysis of the recognition data. The dependent measures are reaction time and accuracy in recognition. The independent measures are working memory span and location-based interference, which was present in Experiment 1A but not in Experiment 1B. Because we did not observe any relevant differences in learning rates for high- and low-span participants, further analysis of the acquisition data were not conducted.

Recognition task

Reaction time

Reaction times for correct responses were submitted to a fan × interference × span mixed-design ANOVA. The test of the full three-way interaction was not significant, $F(2, 164) = 1.56$, $MSE = 52{,}955$, ns. However, even in the absence of that effect, the trends in the data are meaningful. In Fig. 1, high-spans clearly did not differ between experiments and had nearly identical reaction times in Experiments 1A and 1B. Low-spans performed much like high-spans when we controlled for location-based interference in Experiment 1B, but reaction times for the low-spans in Experiment 1A are clearly different from the rest. A significant interference × span interaction provides statistical support for these claims as well, $F(1, 82) = 3.70$, $MSE = 435{,}869$, $p = .05$. There is a simple effect of interference for low-spans but not high-spans. Collapsing across fan, low-spans were significantly faster in Experiment 1B without location-based interference ($M = 1786$ ms, $SE = 72$) than in Experiment 1A ($M = 2150$ ms, $SE = 105$), $F(1, 39) = 8.53$, $MSE = 158{,}051$, $p < .006$. The mean reaction times for high-spans were statistically equivalent in Experiments 1A ($M = 1797$ ms, $SE = 66$) and 1B ($M = 1750$ ms, $SE = 88$), $F(1, 43) < 1.0$, $MSE = 133{,}716$, ns. Additional analyses are reported in Appendix C.

Error rate

Mean errors (see Fig. 1) were submitted to a fan × interference × span mixed-design ANOVA, and the test of the full three-way interaction was significant, $F(2, 164) = 3.14$, $MSE = .875$, $p < .046$. For low-spans, the fan effect slope was significantly greater in Experiment 1A, the interference experiment ($M = .92$, $SE = .11$), than in the absence of location-based interference in Experiment 1B ($M = .34$, $SE = .11$), $F(1, 39) = 14.53$, $MSE = .24$, $p < .001$. The fan effect slopes for high-spans were statistically equivalent in Experiments 1A ($M = .38$, $SE = .06$) and 1B ($M = .27$, $SE = .08$), $F(1, 43) = 1.31$, $MSE = .11$, ns. Additional analyses are reported in Appendix C.

Discussion and interim conclusion

The preceding analyses of errors and reaction times provide collaborating evidence that the difference in slopes for high- and low-span participants depends on the presence of location-based interference. Although we probably lacked the statistical power to detect the interaction among fan × interference × span for reaction times, we argue that a trend toward the desired effect is apparent in Fig. 1 and supported by other significant effects. The significant, between-subjects interaction between interference and span shows that low-spans responded faster in the absence of location-based interference (Experiment 1B) than in its presence (Experiment 1A). Critical, too, is the fact that high-spans performed equivalently between experiments and like the low-spans in Experiment 1B.

Experiments 1A and 1B together support the hypothesis that the ability to control attention in the service of preventing attention to irrelevant episodes, not the amount of LTM activation, accounts for individual

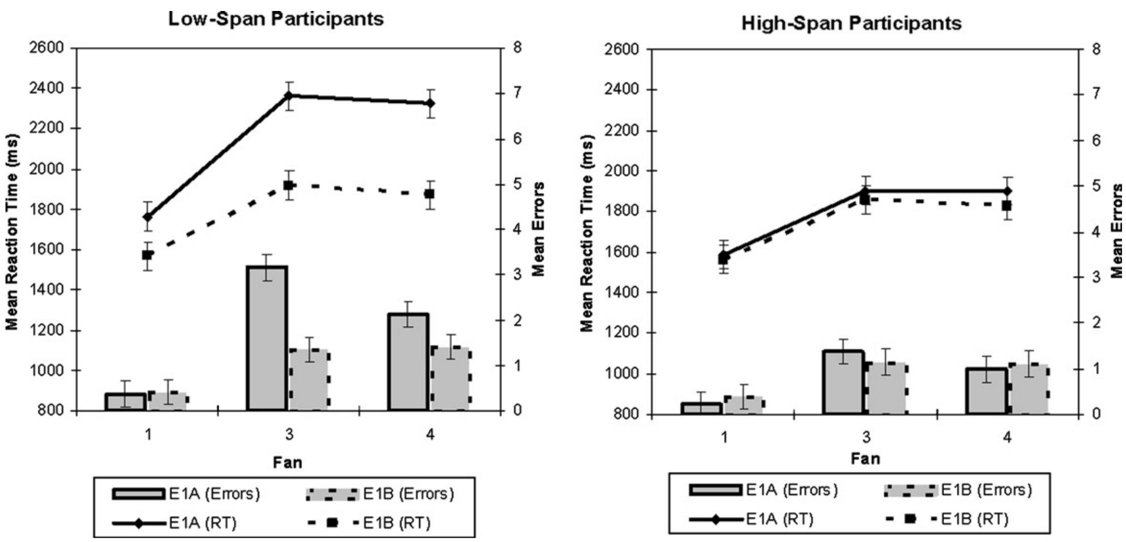

Fig. 1. Between-experiments effects for Experiments 1A and 1B. Mean verification times (in ms) and mean errors for high- and low-span participants as a function of fan size (1, 3, and 4) and the presence (Experiment 1A) or absence (Experiment 1B) of interference from overlapping location-terms. Fan is collapsed across trial type (studied and non-studied items). Bars represent standard error of the mean (RT, reaction time).

differences in the fan effect. All forms of interference were not eliminated in Experiment 1B, but interference from competing learning episodes was removed. This result is consistent with control accounts of working memory. Lustig, May et al. (2001) argued that susceptibility to interference from irrelevant episodes is the crux for why the reading span works the way it does. The results of Experiment 1B seem consistent with that interpretation. The implications of this finding for theories of working memory are discussed further in the General discussion.

Experiment 2A: Interference from person-terms

Location-fan was manipulated between Experiments 1A and 1B (but was held constant within each experiment) while person-fan varied from one, three, and four. We next tested if a similar pattern of results would attain from the manipulation of the presence or absence of overlapping person-terms. Experiment 2A was similar to Experiment 1A with respect to the fact that participants experienced interference both within a learning episode and across episodes. There were significant changes as well. First, the design of Experiment 2A was adjusted to prevent subset relationships. As discussed in Experiment 1A, Cantor and Engle's (1993) smaller fan propositions (Fan 1 and Fan 3) were completely nested within the largest set (Fan 4). This is atypical and may have inadvertently affected how the Fan 4 items were represented. The stimuli for Experiment 2A did not contain complete subset relationships. To accommodate this, fan size was changed from 1, 3, and 4 in Experiments 1A and 1B to 1, 2, and 3 in Experiments 2A and 2B. There was a second significant change with respect to how the stimuli were grouped during learning. In Experiments 1A and 1B, the propositions were presented for study according to the person-terms of the sentences, so that all of the propositions for a person-term were presented together. In Experiments 2A and 2B, the propositions were organized for acquisition according to the location-terms. Location fan varied from 1 to 3, and all of the person-terms associated with a single location were studied together. The person-terms, but not location-terms, overlapped across sets in Experiment 2A. The critical difference between Experiments 2A and 2B was the absence of overlapping person-terms in Experiment 2B (person-terms were associated with just one location).

Method

Participants

Forty-three new participants (22 high-span and 21 low-span; $M(SD)_{\text{span scores}} = 23.36$ (3.20) and 6.90 (2.11), respectively) were selected from a pool of 400 participants who completed operation span. Five additional participants (2 high-span and 3 low-span) were excluded from analyses for not maintaining 63% accuracy on the recognition task.

Materials and procedure

The experimental session lasted 30–45 min. The tasks were computerized, and participants were tested individually.

Acquisition and retention task. Participants learned 12 sentences of the form, *the person is in the location* (see Table 4 for the materials list). Each person was associated with two locations, and each location was associated with one, two, or three people. Hence, person-fan was 1, 2, or 3, and location-fan was 2. Sentences were grouped by the location term (e.g., all sentences for train were presented together). The procedure was otherwise unchanged from Experiment 1A.

Recognition task. The speeded recognition test had four blocks of 24 randomly-ordered trials each (12 studied and 12 non-studied). There was one added criterion for the construction of the fan propositions and non-studied foils. In order to avoid subset relationships, the Fan 1 and Fan 2 items were not completely nested within Fan 3, as was the case in the current Experiment 1A and Experiment 1 of Cantor and Engle (1993). In Experiments 1A and 1B, people were switched between sets of studied sentences so that they still reflected the same fan size. In this experiment, the non-studied items do not reflect the same fan size. The procedure was otherwise unchanged from Experiment 1A.

Results

Data were analyzed from the acquisition and recognition tasks. The dependent measure for the acquisition task was the number of memorization-recall cycles required to meet criterion. The dependent measures for the recognition task were reaction time and accuracy. The independent measures for both were working memory capacity (i.e., span; high and low) and propositional fan size (fan: 1, 2, and 3). Trial type (studied and non-studied sentences) was an additional independent measure in the recognition task.

Acquisition and retention task

As in Experiments 1A and 1B, the low-span group did not require more memorization-recall cycles than the high-span group to meet the acquisition criterion.

Table 4
Studied and non-studied Person and Location pairs in Experiments 2A (●) 2B (□)

Person-terms	Location-terms					
	Boat	Park	Church	Zoo	Store	Train
(1) Studied Person and Location pairs						
Lawyer	● □				●	
Artist		● □		●		
Plumber			● □			●
Teacher			● □		●	
Fireman				● □		●
Coach				□		
Carpenter					□	
Doctor					● □	●
Journalist					□	
Cook						□
Realtor						□
Musician						□
(2) Non-studied Person and Location pairs						
Lawyer				●		● □
Artist			● □		●	
Plumber	●	● □				
Teacher		● □		●		
Fireman	●				● □	
Coach					□	
Carpenter				□		
Doctor	●			● □		
Journalist				□		
Cook	□					
Realtor	□					
Musician	□					

Note. Propositions were of the form, *The person is in the location.*

The mean number of memorization-recall cycles (see Table 2) for each level of span was submitted to a fan × span mixed-design ANOVA. There was a fan effect for learning, $F(2, 82) = 6.86$, $MSE = 0.20$, $p < .01$, but there was neither a main effect of span nor an interaction between fan and span, $F(1, 41) < 1.0$, $MSE = 0.28$, and $F(2, 82) < 1.0$, $MSE = 0.53$, respectively.

Recognition task

Reaction time. Mean reaction times for correct responses (see Table 5) were submitted to a fan × span × trial type mixed-design ANOVA. The test of the full three-way interaction approached significance, $F(2, 80) = 2.47$, $MSE = 58{,}772$, $p = .09$. The fan effects for studied and non-studied items slope in opposite directions, and the results are most meaningful and interpretable if these items are analyzed separately. There were significant fan × span interactions for studied and non-studied items, $F(2, 82) = 4.75$, MSE = 39,465, p < .01, and $F(2, 82) = 4.61$, MSE = 85,660, p < .01, respectively. The effect sizes (ω^2) for these interactions were .15 and .14, respectively. Slope provides a measure of the magnitude of the fan effects for high- and low-spans. The fan effect slope for reaction times to studied items was greater for low-spans ($M = 266$, $SE = 37$) than high-spans ($M = 139$, $SE = 26$), $t(df = 41) = 2.86, p < .007$. This result is consistent with our observations in Experiment 1A. Negative fan effects were obtained for non-studied items, but the difference between the slopes of the fan effects for high-spans ($M = -216$, $SE = 46$) and low-spans ($M = -160$, $SE = 51$) failed to reach significance, $t(df = 41) < 1.0$, ns. In the case of negative fan effects, steeper slopes are indicative of faster reaction times; therefore, the pattern of results, with a steeper negative slope for high-spans, is consistent with the findings for studied items. Additional analyses are reported in Appendix D.

Error rate. Mean errors during verification (see Table 5) were submitted to an analysis like that for the reaction time data. There was an interaction between fan and trial type, $F(2, 82) = 10.95$, $MSE = 1.43$, $p < .001$. The slope of the fan effect was positive and significantly different from zero for studied items, but it was negative and significantly different from zero for non-studied items. However, working memory span was unrelated to the errors made, as indicated by the absence of a fan × span × trial type interaction or a fan × span interaction, $F(2, 82) < 1.0$, $MSE = 1.43$, ns, and $F(2, 82) < 1.0$, $MSE = 1.06$, ns, respectively. Additional analyses are reported in Appendix D.

Discussion

Results from Experiment 2A were consistent with our findings in Experiment 1A and Cantor and Engle's (1993) Experiment 1. Working memory span was related to the speed and accuracy with which propositions were retrieved from semantic memory, but not the rate at which the propositions were learned. On studied items in the recognition task, both span groups revealed fan

Table 5
Means (and *SD*) for correct response times and error rates to studied and non-studied items on the recognition test of Experiments 2A and 2B for high- and low-span participants

Probe type	Response times (in ms)			Mean errors		
	Fan 1	Fan 2	Fan 3	Fan 1	Fan 2	Fan 3
Experiment 2A						
High span						
Studied	1346 (371)	1529 (400)	1623 (448)	.23 (.53)	1.36 (1.53)	1.36 (1.36)
Non-studied	2063 (834)	1710 (404)	1631 (519)	1.00 (1.11)	.55 (1.18)	.55 (1.01)
M	1704 (588)	1619 (375)	1627 (463)	.61 (.62)	.95 (.92)	.95 (1.03)
Low span						
Studied	1408 (231)	1781 (336)	1940 (316)	.48 (.75)	1.29 (1.27)	1.52 (1.54)
Non-studied	1961 (545)	1981 (440)	1641 (208)	1.05 (1.02)	1.05 (1.07)	.38 (.67)
M	1685 (343)	1881 (359)	1790 (237)	.76 (.56)	1.17 (.81)	.95 (.74)
Experiment 2B						
High span						
Studied	1142 (209)	1388 (380)	1487 (507)	.23 (.53)	.50 (.80)	.50 (.67)
Non-studied	1277 (253)	1499 (404)	1468 (321)	.32 (.78)	.50 (.67)	.64 (.73)
M	1210 (219)	1443 (376)	1477 (391)	.27 (.48)	.50 (.51)	.57 (.47)
Low span						
Studied	1205 (232)	1467 (316)	1571 (325)	.61 (.84)	.65 (.98)	1.22 (2.02)
Non-studied	1477 (302)	1604 (423)	1537 (311)	.26 (.54)	.91 (1.13)	.87 (1.36)
M	1341 (239)	1535 (357)	1554 (288)	.43 (.57)	.78 (.96)	1.04 (1.22)

effect slopes for reaction times and errors that were positive and significantly different from zero, but the low-span group had greater slopes than the high-span group. The fan effect slopes for reaction times and errors on the non-studied items were negative, but the outcome was still the same: the high-span group was faster and more accurate than the low-span group.

The negative fan effect for non-studied items is atypical, and although it may complicate our results, we do not think that it compromises them. The negative fan is evidence that participants organized the items in memory by location-terms and not person-terms. We see in Table 4 that there were three studied and one non-studied propositions for the location, train. When given the non-studied cue, *the lawyer is in the train?*, it seems likely that participants checked their memory against the three studied person-train propositions. The opposite would be true for the location, boat, which was associated with one studied and three non-studied propositions. When given a non-studied boat cue, it seems likely that memory was checked against the one studied proposition. It is faster to check memory against one proposition (the boat example) than three (the train example); consequently, a negative fan for non-studied items was attained. A better design, which would have prevented the negative fan from occurring, would have had the same number of studied and non-studied items for each location, as was the case in the Experiment 1A materials. For example, the location, boat, should have been associated with one studied and one non-studied proposition, while the location, train, should have been associated with three studied and three non-studied propositions. This oversight does not change our primary finding about individual differences in working memory and the fan effect.

The location-terms in Experiment 2A were associated with 1, 2, or 3 different person-terms, and each person-term was associated with two different locations. As a test of the attentional control hypothesis in Experiment 2B, cross-episode, person-term interference was eliminated and each location was paired with a unique set of person-terms.

Experiment 2B: No interference from person-terms

Method

Participants

Forty-five new participants (22 high-span and 23 low-span; $M(SD)_{\text{span scores}} = 22.09$ (5.91) and 6.13 (2.52), respectively) were selected from the same pool of participants prescreened on operation span in Experiment 2A. All participants met the 63% accuracy criterion on the recognition task.

Materials and procedure

The materials and procedure were unchanged from Experiment 2B, with the exception that there was no overlap among person-terms (person-fan = 1). The studied and non-studied materials are shown in Table 4.

Results

The independent and dependent variables were the same as those for Experiment 2A.

Acquisition and retention task

As in all previous experiments, the low-span group did not require more memorization-test cycles to meet the acquisition criterion than the high-span group. The mean number of memorization-recall cycles (see Table 2) for each level of span was submitted to a fan × span mixed-design ANOVA. There was a fan effect, but there was neither a main effect of span nor an interaction between fan and span, $F(2,86) = 13.93$, $MSE = .20$, $p < .001$, $F(1,43) = 2.02$, $MSE = .32$, ns, and $F(2,86) < 1.0$, $MSE = .32$, ns, respectively.

Recognition task

Reaction time. Mean correct reaction times (see Table 5) were submitted to a fan × span × trial type mixed-design ANOVA. Working memory span was unrelated to the fan effect for reaction times. Neither the test of the full three-way interaction nor the interaction between fan and span were significant, $F(2, 86) = 1.13$, $MSE = 31{,}367$, ns, and $F(2,86) < 1.0$, $MSE = 53{,}193$, ns. For consistency with our decision to analyze studied and non-studied items separately in Experiment 2A, we can perform separate analyses for both trial types without any effect on the outcome. For studied and non-studied items, the fan × span interactions were not significant, $F(2,86) < 1.0$, $MSE = 50{,}441$, ns, and $F(2, 86) = 1.52$, $MSE = 34{,}119$, ns, respectively. The effect sizes (ω^2) for these interactions were .01 and .02, respectively. However, the failure to find these effects is not due to a lack of power. The power (by charts from Pearson & Hartley, 1972) was .98 to detect an effect size of .14 or .15, which were the effect sizes for the critical effects in Experiment 2A. Although fan was unrelated to span, the slope of the fan effect for reaction times was significantly greater than zero, as indicated by a main effect of fan, $F(2,86) = 29.44$, $MSE = 53{,}193$, $p < .001$. Additional analyses are reported in Appendix E.

Error rate. Mean errors (see Table 5) were submitted to a fan size × span × trial type mixed-design ANOVA. As in the analysis of reaction times, working memory span was unrelated to the fan effect for errors. There was a main effect of fan, but there was neither an interaction between fan and span nor among fan, span, and trial type, $F(2,84) = 5.89$, $MSE = .84$, $p < .005$, $F(2,86) < 1.0$,

$MSE = .84$, ns, and $F(2, 86) < 1.0$, $MSE = .89$, ns, respectively. Additional analyses are reported in Appendix E.

Discussion

Working memory span determined the slope of the fan effect for reaction times on studied items in Experiment 2A. However, Experiment 2B demonstrated that this effect was contingent upon interference from competing learning episodes. The fan propositions were studied in sets organized by the location-terms, which were not repeated across sets in either 2A or 2B. Person-terms were repeated across sets in 2A. Interference from competing sets proved detrimental to low-spans but not high-spans, for low-spans could perform like high-spans when that type of interference was removed.

The presence of a main effect for fan is consistent with previous research, including Radvansky et al.'s (1993) theory on situation models. Unlike the materials in Experiment 1B where a single person was associated with multiple locations, the materials in the current experiment involved multiple people in a single location. Therefore, it is conceivable that participants could form a unique situation model for each location, just as was the case for multiple objects in a single location in Radvansky et al. (1993, Experiment 1). The fact that there is still a fan effect in our current experiment could be attributed to the fact that the materials were still not suggestive of one type of situation over another. As in our Experiment 1B and in Radvansky et al.'s Experiment 3, these particular person and location-terms do not easily give rise person-based or location-based situation models.

As was the case for Experiments 1A and 1B, our assumptions about the effects of interference and the results in Experiment 2A and 2B are dependent upon the outcome of some between-experiments analyses. More specifically, we know from the previous analyses that all participants showed fan effects for reaction times in these experiments. However, based on an attentional control view of working memory, we would expect the low-span groups to differ between experiments as a result of the presence of person-based interference in Experiment 2A. Further analyses should reveal steeper, positively sloped fan effects for reaction times for low-span participants in the interference condition (Experiment 2A) than in the non-interference condition (Experiment 2B). The high-span groups should have comparable fan effect slopes between experiments.

Experiments 2A and 2B: Between-experiments analyses

Interpretation of the data in Experiment 2A was complicated by the fact that the fan effects for reaction times sloped in opposite directions on the studied and non-studied items. Our solution was to analyze studied and non-studied items separately, and we did so again here for ease of interpretation. The pertinent independent measures are working memory span and person-based interference, which was present in Experiment 2A and absent from Experiment 2B. The dependent measure is reaction time. We will not further analyze errors on the verification task or the acquisition data, because high- and low-span participants did not differ on these measures in either Experiment 2A or 2B.

Results

Recognition task

Reaction time. Studied and non-studied items were analyzed separately. For studied items (see Fig. 2), the mixed design ANOVA for the interaction of fan × interference × span approached significance, $F(2, 168) = 2.51$, $MSE = 45{,}084$, $p = .07$. As predicted, the fan effect slope for low-spans was greater in the interference condition (Experiment 2A; $M = 266$, $SE = 37$) than in the non-interference condition (Experiment 2B; $M = 183$, $SE = 27$), $t(df = 42) = 1.88$, $p = .07$. The fan effect slopes for high-spans were statistically equivalent in the interference ($M = 139$, $SE = 26$) and the non-interference conditions ($M = 172$, $SE = 47$), $t(df = 42) < 1.0$, ns.

For non-studied items (see Fig. 3), the fan × interference × span interaction was significant, $F(2, 168) = 5.10$, $MSE = 59{,}276$, $p < .007$. In previous analyses, we saw that there was a fan × span interaction for reaction times on non-studied items in Experiment 2A but not in Experiment 2B.

Discussion

The results of Experiments 2A and 2B and the subsequent between-experiments analyses show that the presence of person-based interference caused low-spans to be slower even when their responses were accurate. Location-based interference was not manipulated between experiments and caused fan effects by its presence. However, this form of interference was unrelated to span, probably because the fan propositions were learned in sets grouped by the location-terms. The results of Experiments 2A and 2B are consistent with an attentional control view of working memory. Engle's controlled attention view and Hasher's inhibition view make similar predictions for the effects of interference on span groups (Engle, 2001; Lustig, May et al., 2001). These results are consistent with those theories of working memory capacity, but not earlier theories such as the general capacity that attempted to quantify working memory capacity in terms of an amount of memory capacity.

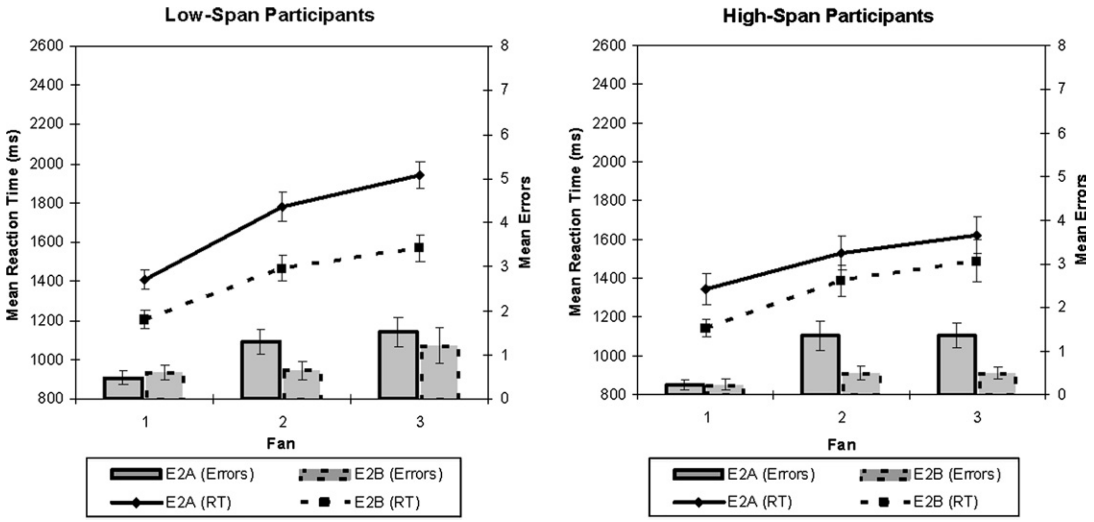

Fig. 2. Between-experiments effects for studied items in Experiments 2A and 2B. Mean verification times (in ms) and mean errors for high- and low-span participants as a function of fan size (1, 2, and 3) and the presence (Experiment 2A) or absence (Experiment 2B) of interference from overlapping person-terms. Bars represent standard error of the mean (RT, reaction time).

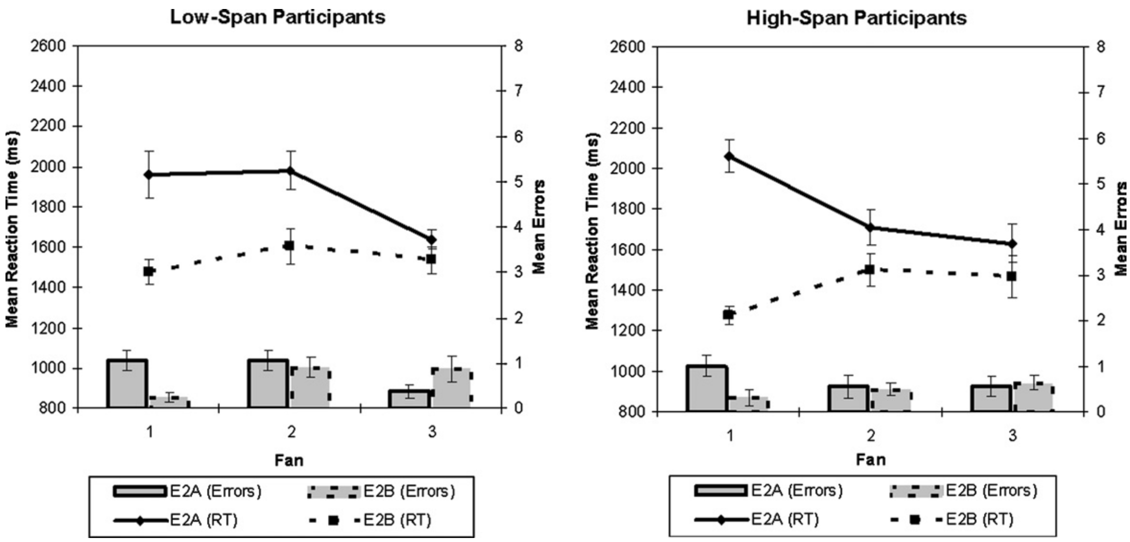

Fig. 3. Between-experiments effects for non-studied items in Experiments 2A and 2B. Mean verification times (in ms) and mean errors for high- and low-span participants as a function of fan size (1, 2, and 3) and the presence (Experiment 2A) or absence (Experiment 2B) of interference from overlapping person-terms. Bars represent standard error of the mean (RT, reaction time).

General discussion

Four experiments demonstrated that individual differences in working memory capacity are related to performance in the fan paradigm when there are multiple sources of response competition (i.e., from person- and location-terms), but more specifically, when there is interference across learning sets. This type of interference was detrimental to the low-span group, who tended to make more errors and slower responses (see Experiments 1A and 2A). However, when interference from competing learning sets was removed, the low-span group was indistinguishable from the high-span group, even though an interference effect remained from the presence of multiple items within a learning set (see Experiments 1B and 2B).

The ability to resist interference, not a limited amount of activation, is the critical determinant of individual differences in the fan effect. According to Hasher and colleagues, interference from prior and irrelevant items is detrimental to groups that show working memory deficits, such as older adults in many of their studies (Lustig, May et al., 2001; May et al., 1999). Our findings are consistent with this view of working memory capacity. Individual differences in working memory capacity appear in conditions in which there is interference from irrelevant items, such as interference from across learning sets in our experiments with the fan paradigm.

This interpretation is also consistent with the controlled-attention of view of working memory (Engle, 2001), which represents a definite transition from the earlier general-capacity view (Cantor & Engle, 1993; Engle et al., 1992; Turner & Engle, 1989). According to both the general-capacity and controlled-attention theories, working memory is a subset of long-term declarative memory; that is, it is the temporary or permanent knowledge units in long-term memory that are currently active. But, the controlled attention view emphasizes the attentional processes that achieve and maintain activation, especially under conditions of interference. Consequently, individual differences in working memory capacity are related to: (1) the ability to control the activation of relevant information, and (2) the ability to block activation of distracting information. This clearly applies to the present experiments. High-spans succeeded (in terms faster responses and greater accuracy) as a result of better control and an ability to block activation of irrelevant fan responses.

Future research could strengthen the arguments we have presented here. One possibility is to devise an experiment in which the fan propositions are studied individually and not in sets. Doing so might dissuade participants from employing chunking strategies as discussed in Experiment 1A. Person- and location-terms might then both provide the kind of cross-episodes interference that seems detrimental to low-span participants. The trick will be to find fan propositions that are not easily integrable and consequently not easily represented by handy mnemonics.

Finally, it has been argued that working memory is a theoretically loaded term (Neath, 1998). It implies a distinction between active and inactive memory, relies heavily on the notion of spreading activation, and most, though not all, models of working memory assume that forgetting is a function of both decay and interference. While the working memory framework clearly motivated our research, it is not necessary to assume a working memory system to interpret the results reported here. We observed that operation span predicted performance in the fan paradigm when interference from competing learning episodes was present. When this interference was reduced, performance in the fan paradigm was related to working memory span. Thus, rather than assume a working memory system, one might simply conclude from these experiments that individuals differ in their ability to resolve interference in cognitive tasks, and this ability is what cognitive psychologists have been calling working memory capacity. It is important to note that this ability and this correlation are not trivial, as performance on span tasks similar to operation span is highly correlated with a wide range of complex cognitive behaviors such as reading comprehension, problem solving, and reasoning. Further, this ability, which has been called working memory capacity, is a strong predictor of general fluid intelligence (Conway et al., 2002; Engle, Tuholski et al., 1999; Kyllonen & Chrystal, 1991). Thus, the relationship between performance in operation span and the fan task observed here reflects an ability that is critical for cognition.

Appendix A. Remaining analyses: Experiment 1A

Remaining reaction time analyses

There were main effects of fan, span, and trial type, $F(2,80) = 37.69$, $MSE = 146{,}983$, $p < .005$, $F(1,40) = 8.77$, $MSE = 888{,}354$, $p < .001$, and $F(1,40) = 74.62$, $MSE = 75{,}446$, $p < .001$, respectively. There was neither an interaction between fan and trial type nor between span and trial type, $F(2,80) = 2.05$, $MSE = 42{,}796$, ns, and $F(1,40) = 3.38$, $MSE = 75{,}446$, ns, respectively.

Remaining error analyses

There were main effects of fan and span, $F(2,80) = 49.72$, $MSE = 1.67$, $p < .001$, and $F(1,40) = 20.12$, $MSE = 3.30$, $p < .001$. There was neither an interaction between fan and trial type nor between span and trial type, $F(2,80) = 2.46$, $MSE = 1.92$, ns, and $F(1,40) < 1.0$, $MSE = 2.22$, respectively. There was no main effect of trial type, $F(1,38) = 3.01$, $MSE = 2.22$, ns.

Appendix B. Remaining analyses: Experiment 1B

Remaining reaction time analyses

There was a main effect of trial type, $F(1,42) = 39.95$, $MSE = 44{,}478$, $p < .001$. There was an interaction between fan and trial type, $F(2,84) = 12.08$, $MSE = 49{,}226$, $p < .001$. There was neither a main effect of span nor an interaction between span and trial type, $F(1,42) < 1.0$, $MSE = 885{,}914$, ns, and $F(1,42) < 1.0$, $MSE = 44{,}119$, ns, respectively.

Remaining error analyses

There was an interaction between fan and trial type, $F(2,84) = 3.14$, $MSE = 1.49$, $p < .0015$. There was neither a main effect of span nor trial type, $F(1,42) < 1.0$, $MSE = 3.56$, ns, and $F(1,42) = 3.14$, $MSE = 1.23$, ns, respectively. There was not an interaction between span and trial type, $F(1,42) < 1.0$, $MSE = 1.23$, ns.

Appendix C. Remaining analyses: Between-experiments 1A and 1B

Remaining reaction time analyses

There were main effects of fan, interference, and span, $F(2,164) = 76.10$, $MSE = 52{,}955$, $p < .001$, $F(1,82) = 6.22$, $MSE = 435{,}869$, $p < .0012$, and $F(1,82) = 5.60$, $MSE = 435{,}869$, $p < .0012$. The interactions between fan and interference and between fan and span were significant, $F(2,164) = 2.78$, $MSE = 52{,}955$, $p = .06$, and $F(2,164) = 3.32$, $MSE = 52{,}955$, $p < .0014$.

Remaining error analyses

There were main effects of fan, interference, and span, $F(2,164) = 52.85$, $MSE = .88$, $p < .001$, $F(1,82) = 6.02$, $MSE = 1.71$, $p < .0012$, and $F(1,82) = 13.78$, $MSE = 1.71$, $p < .001$. There were significant interactions between the following: fan × interference, fan × span, and interference × span, $F(2,164) = 7.86$, $MSE = .88$, $p < .001$, $F(2,164) = 5.44$, $MSE = .88$, $p < .01$, and $F(1,82) = 6.76$, $MSE = 1.71$, $p < .0011$.

Appendix D. Remaining analyses: Experiment 2A

Remaining reaction time analyses

When studied and non-studied items were included in the same analysis, there was a main effect of trial type, $F(1,41) = 35.99$, $MSE = 92{,}073$, $p < .001$. The following interactions were significant: fan × span, span × trial type, and fan × trial type, $F(2,80) = 6.59$, $MSE = 66{,}353.18$, $p < .001$, $F(1,41) = 3.96$, $MSE = 92073.28$, $p = .05$, and $F(2,82) = 56.02$, $MSE = 58{,}772.34$, $p < .001$. There was neither a main effect of fan nor span, $F(2,82) = 1.08$, $MSE = 66{,}353$, ns, and $F(1,41) = 1.33$, $MSE = 880{,}595$, ns, respectively.

When studied and non-studied items were analyzed separately, there were main effects of fan and span for studied items, $F(2,82) = 46.56$, $MSE = 39{,}465$, $p < .001$, and $F(1,41) = 4.65$, $MSE = 305{,}894$, $p < .04$, respectively. For non-studied items, there was a main effect of fan but not span, $F(2,82) = 17.82$, $MSE = 85{,}600$, $p < .001$, and $F(1,41) < 1.0$, $MSE = 666{,}774$, ns, respectively.

Remaining error analyses

There were main effects of fan and trial type, $F(2,82) = 2.98$, $MSE = 1.06$, $p = .06$, and $F(1,41) = 5.19$, $MSE = .97$, $p < .03$, respectively. There was no effect of span, $F(1,38) < 1.0$, $MSE = 1.72$. There was no interaction between span and trial type, $F(1,41) < 1.0$, $MSE = .97$, ns.

Appendix E. Remaining analyses: Experiment 2B

Remaining reaction time analyses

When studied and non-studied items were included in the same analysis, there was a main effect of trial type, $F(1,43) = 24.14$, $MSE = 28{,}187$, $p < .05$. There was an interaction between fan and trial type, $F(2,86) = 9.72$, $MSE = 28{,}187$, $p < .05$. There was neither an effect of span nor an interaction between span and trial type, $F(1,43) = 1.13$, $MSE = 502{,}050$, ns, and $F(1,43) = 1.45$, $MSE = 31{,}367$, ns.

When studied items were analyzed separately, there was a main effect of fan but not one of span, $F(2,86) = 29.87$, $MSE = 50{,}441$, $p < .001$, and $F(1,43) < 1.0$, $MSE = 248{,}969$, ns, respectively. When non-studied items were analyzed separately, there was a main effect of fan but not of span, $F(2,86) = 10.68$, $MSE = 34{,}119$, $p < .01$, and $F(1,43) = 1.66$, $MSE = 281{,}267$, ns.

Remaining error analyses

There was neither a main effect of span nor trial type, $F(1,43) = 2.54$, $MSE = 1.36$, ns, and $F(1,43) < 1.0$, $MSE = .73$, ns, respectively. There was neither an interaction between span and trial type nor fan and trial type, $F(1,43) < 1.0$, $MSE = .73$, ns, and $F(2,86) < 1.0$, $MSE = .71$, ns.

Appendix F. Remaining analyses: Between Experiments 2A and 2B

Remaining reaction time analyses

For studied items, there were main effects of fan, interference, and span, $F(2,168) = 74.05$, $MSE = 45{,}004$, $p < .001$, $F(1,84) = 4.85$, $MSE = 276{,}754$, $p < .0013$, and $F(1,84) = 12.37$, $MSE = 276{,}754$, $p < .001$, respectively. The interaction between fan and span approached significance, $F(2,168) = 2.51$, $MSE = 45{,}004$, $p = .08$. The interactions between fan and interference and between interference and span were not significant, $F(2,168) < 1.0$, $MSE = 45{,}004$, ns, and $F(1,84) = 1.08$, $MSE = 276{,}754$, ns, respectively.

For non-studied items, there were main effects of fan and interference but not span, $F(2,168) = 7.98$, $MSE = 59{,}276$, $p < .001$, $F(1,84) = 17.62$, $MSE = 469{,}431$, $p < .001$, and $F(1,84) = 1.19$, $MSE = 469{,}431$, ns. The interaction between fan and interference was significant, and the fan × span interaction approached significance, $F(2,168) = 24.36$, $MSE = 59{,}276$, $p < .001$, and $F(2,168) = 2.57$, $MSE = 59{,}276$, $p = .08$. The interaction between interference and span was not significant, $F(1,84) < 1.0$, $MSE = 469{,}431$, ns.

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