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Working Memory Capacity and Suppression

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Two experiments examined whether a relationship exists between an individual's working memory capacity and their ability to suppress intrusive thoughts and behaviors. In both experiments, participants learned three lists in a modified paired-associates task where the interference condition followed an AB–AC–AB design and the noninterference condition an EF–DC–AB design. Experiment 1 stressed speed, and individuals who scored high on a measure of working memory capacity (high spans) produced fewer first-list intrusions during second-list learning than did low spans. Experiment 2 stressed accuracy, and high spans in the interference condition were slower than their control to retrieve first-list responses on List 3, suggesting that they had suppressed them during second-list learning. In contrast, the low spans in the interference condition were faster than their control. The findings suggested that a relationship exists between an individual's working memory capacity and their ability to suppress intrusive thoughts and behaviors. © 1998 Academic Press

Performance on tests of working memory capacity correlate with a wide variety of general, higher level cognitive tasks (Engle, 1996). Relationships have been found between complex span measures and performance on tasks involving reading comprehension (Daneman & Carpenter, 1980, 1983); language comprehension (King & Just, 1991; MacDonald, Just, & Carpenter, 1992); vocabulary learning (Daneman & Green, 1986); following directions (Engle, Carullo, & Collins, 1991); reasoning (Kyllonen & Christal, 1990); and complex learning (Shute, 1991; Kyllonen & Stephens, 1990). Although these findings are important in and of themselves, they do not inform us as to the mechanisms responsible for the relationships.

In a series of papers, Engle and colleagues have argued that individual differences in working memory capacity reflect differential abilities to bring domain-free, focused attention to bear on cognitive tasks (Conway & Engle, 1994; Engle, 1996; Rosen & Engle, 1997). Thus, measures of working memory capacity such as those developed by Daneman and Carpenter (1980) and Turner and Engle (1989) are assumed to be valid measures of constructs such as the central executive proposed by Baddeley and Hitch (1974) and the supervisory attentional system proposed by Shallice and his colleagues (Norman & Shallice, 1986; Shallice & Burgess, 1991). We have argued that working memory or central executive capacity will not be important to all forms of information processing. For ex-

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ample, it is now clear that much of our processing can and does occur relatively automatically (Shiffrin, 1988) and individual differences in working memory capacity will *not* be reflected in those situations. However, individual differences in working memory capacity will be important in performance of a task to the extent that: (1) information must be maintained for a brief period of time in the face of distraction or interference, (2) strategic, controlled search is beneficial for the task, (3) monitoring for errors is required because elements of the task automatically induce thoughts or behaviors inappropriate to the current task, and (4) task performance would be improved by the suppression of those inappropriate thoughts or behaviors. It is this last characteristic that is the focus of the present work.

Baddeley and Hitch (1974) conceived of the central executive as a mental workspace for the simultaneous processing and storage of information. However, we believe that another function of the central executive may be to suppress task-irrelevant information (Conway & Engle, 1994; Engle, Conway, Tuholski, & Shisler, 1995; Rosen & Engle, 1997). Therefore, we would expect to find that individuals who score high on a measure of working memory capacity or controlled attention (i.e., high span individuals) would also be better able to inhibit or suppress interfering information than would individuals who score low on the same measure (i.e., low span individuals). In a set of four studies, Rosen and Engle (1997) examined the role of working memory capacity in retrieval by having low and high span individuals retrieve exemplars from the animals category for 10 minutes. In such category fluency tasks, individuals typically retrieve words in clusters where the retrieval times between the words within a cluster are much shorter than the retrieval times between the clusters. In each of the four experiments, the high span participants retrieved more unique animal names over the period than did the low span participants. Although the size of a cluster was not much different for the two groups, the retrieval time between the clusters was much longer for the low span participants. These findings were evident even in the first minute, when knowledge base differences should have exerted little effect. Further, low span participants tended to make more intrusions of already retrieved names. Our interpretation of the longer between-cluster retrieval times was that the low span participants experienced difficulty accessing new names because of covert intrusions from the animal names that had been previously retrieved. In contrast, the high span participants were not as hampered by previously retrieved names because they had suppressed them. The purpose of the studies described here is to further examine whether individuals who differ on a measure of working memory capacity show corresponding differences in their vulnerability to intruding thoughts and behaviors, and their ability to suppress them.

Inhibition and suppression are constructs that have a long history in psychology (Diamond, Balvin, & Diamond, 1963) but they did not fit well with either the behaviorist tradition (Donahoe & Palmer, 1988), or the computer metaphor of mind, so there was little discussion of them in modern literature until recently (Bjork, 1989). As a result of neural network and other brain-oriented approaches to cognition, the concepts of inhibition and suppression are now used commonly in theories of cognition. Inhibition has been seen as an important player in working memory (Conway & Engle, 1994; Rosen & Engle, 1997; Hasher & Zacks, 1988), aging (Hasher, Stoltzfus, Zacks, & Rypma, 1991; Hasher & Zacks, 1988), selective attention (Neill, 1977; Neill, Valdes, & Terry, 1995; Tipper & Cranston, 1985), language processing (Gernsbacher & Faust, 1991; Neill, 1989), and retrieval (Anderson & Bjork, 1994; Bjork, 1989; Roediger & Neely, 1982; Rosen & Engle, 1997). One presumed benefit of suppression or inhibition of distracting thoughts or behaviors is reduced vulnerability to interference. Further, differential ability to resist interference has been proposed as an explanation for individual and developmental differences in cognition (Dempster, 1985, 1991, 1992; Dempster & Cooney, 1982; Hasher & Zacks, 1988). A decrease in resistance to interference has also been argued to follow from certain types of brain damage, particularly frontal lobe damage (Dempster, 1991, 1992; Shimamura, Jurica, Mangels, Gershberg, & Knight, 1995).

The paired-associates task has been used recently to study differences in resistance to interference among neurological patient groups and normals (Shimamura et al., 1995; Uhl, Franzen, Serles, Lang, Lindinger, & Deecke, 1990; Winocur & Moscovitch, 1983). We chose the paired-associates task to test for the role of working memory capacity in suppression because we could easily modify it to examine both interference from intrusions and the suppression of intrusions. However, in using a paired-associates task, we run the risk of confusing the central issue of the paper (i.e., the relationship between working memory capacity and suppression) with traditional verbal learning issues (i.e., the nature of proactive and retroactive interference). Therefore, we will only briefly describe the paired-associates task and its history in order to provide some background for the paired-associate methodology that we borrowed. In the traditional paired-associates task, individuals learn two or more lists containing pairs of cue–response items. Let us give an example of the alphabetic nomenclature that is traditionally used to describe the paired-associates task. Participants may learn a list of pairs such as *table–car, queen–donkey,* etc. The task is to subsequently recall *car* when presented with *table, donkey* when presented with *queen,* etc. We will designate *table* and *queen* as the cue or A words and *car* and *donkey* as the response or B words. This would be the AB list. Interference is introduced by then having the participant learn a subsequent list in which the cue words remain the same but the response words change leading to pairs such as *table–boat, queen–pony,* etc. This would be the AC list.

Subsequent to Melton and Irwin (1940), the paired-associates task became the preferred method of testing for the locus of interference and forgetting. The two types of interference that are traditionally examined in the paired-associates task are proactive and retroactive interference. Proactive interference is tested for by having a delayed recall test of the C items follow the learning of the AC list. Evidence for proactive interference is seen as a reduction in the number of C items recalled after having learned a related first list (i.e., AB), when compared to the recall of the same C items after having learned an unrelated first list or no first list at all. More recent paired-associate studies have examined the number of trials to learn AC, or performance on the first trial of learning AC, for evidence of proactive interference (Anderson, 1981; Shimamura et al., 1995). These last two measures were traditionally referred to as measures of negative transfer and not proactive interference, because they reflect whether and how learning one list interferes with the learning of a second list. In the present set of experiments, we also examined the number of trials to learn the AC list in the AB–AC interference condition compared to a control condition that learned an unrelated first list. However, our primary interest in this measure was to determine whether individuals would differ in the amount of interference they experienced from intruding first-list items and not whether and how a first list interferes with the learning of a second list. Consequently, in the interest of maintaining focus on the central issue of this paper, we will refrain from using verbal learning terminology to describe interference effects in the present set of experiments. The second type of interference that was examined in the traditional paired-associates task is retroactive interference. Retroactive interference is tested for by examining retention of first-list responses after having learned a related or unrelated second list. Because we were interested in examining suppression rather than retention of first-list responses, we did not test for retroactive interference in these studies.

The present set of studies was motivated by two questions concerning the relationship between working memory capacity and suppression. First, do individuals who differ on a measure of working memory capacity also differ in their vulnerability to intruding thoughts and behaviors? In other words, does a relationship exist between an individual's working memory capacity and the number of covert intrusions they experience? Second, does a relationship exist between an individual's working memory capacity and their ability to suppress intrusions? Because we were interested in examining suppression of intrusions, we endeavored to maximize response competition, and resultant intrusions, in two ways. First, in the interference condition, we used a single category and an identical set of 12 cue words on each of the three lists that participants would learn. Second, first-list pairs were constructed from compound words having strong prior associations (e.g., bird–bath), whereas second-list pairs were constructed from the same cue words paired with response words that did not have strong prior associations with the cue words (e.g., bird–dawn). The combination of strong prior AB associations and overlearning of each pair was expected to result in a high level of response competition between first and second-list response items that shared the same cue words. Consequently, when cued with the A term *bird* during the learning of the AC list, *bath* should quickly come to mind even though the correct response would be *dawn*.

As a further modification to the paired-associates task, we used a nontraditional control condition to test for suppression of first-list response items. Traditional paired-associate studies had their interference and control conditions learn the same first and third lists. The use of an identical first list for both conditions, along with different second lists, makes perfect sense if the goal is to determine whether interference from a second list contributes to forgetting of a first list (i.e., retroactive interference). In contrast, we were interested in examining whether individuals differed in their ability to suppress first-list intrusions, during second-list learning. Because we had participants overlearn each list, as one way to maximize response competition between lists we expected that first-list retention would be high and so would not be a sensitive measure of suppression. Therefore, we examined vocal response time as a measure of suppression. Consequently, we needed to test for suppression against a control condition in which participants retrieved the same first-list response items for the very first time after having learned two previous unrelated lists. Otherwise, we would have been testing for suppression against a control condition that was experiencing the benefit of a repetition effect. Repetition effects could bias group differences in the direction of suppression. Consequently, we chose to use a more conservative control condition than that used in traditional paired-associates studies.

Four measures were examined in both experiments: (1) number of trials to reach criterion on a list, (2) number of overt intrusions per trial, (3) vocal response latency, and (4) percent correct recall. However, we focused on a different subset of these measures in each experiment, depending on whether we were examining span differences in vulnerability to intrusions (Experiment 1) or span differences in suppression of intrusions (Experiment 2). Number of intrusions is commonly low in the paired-associates task. Therefore, we increased the likelihood that participants would produce intrusions in Experiment 1 by emphasizing speed and using a response deadline of 1350 ms. We arrived at this deadline in a pilot study that was directed at finding a response window that was long enough to allow both low and high span participants to produce a response word when presented with a cue word, while still short enough to prevent them from correcting their responses during production. The combination of speed instructions and a response deadline was designed to encourage a rapid response at a point where response competition should be strong, thereby increasing the likelihood that the participant would vocalize intrusions. Consequently, span differences in accuracy rates would preclude us from examining vocal response time as a measure of interference. Therefore, we examined the mean number of trials to reach criterion, and the mean number of intrusions produced per trial on the second list, as our measures of interference due to intrusions. The second experiment was directed at span differences in the suppression of intrusions. Therefore, the Experiment 2 instructions strongly emphasized accuracy, and participants were allowed 32 s to provide a response word when presented with the cue word so that there would be sufficient time to covertly suppress any intruding first-list items. Consequently, we expected to find a high level of recall accuracy for both the low and high span participants so that number of intrusions and trials to reach criterion would not be sensitive measures of suppression. Therefore, we examined vocal response time as our measure of suppression.

GENERAL METHOD

The following procedures were common to both experiments.

Participants

All participants were undergraduate students from the University of South Carolina. They received course credit in exchange for participation. Participants were chosen for low and high working memory span groups based on their operation span score. High span participants were those participants who scored in the upper quartile of the distribution of operation span scores during the academic semester, whereas low span participants were those who scored in the lower quartile of the same distribution of scores.

Operation span task. Participants in both experiments were prescreened on a variation of the operation span task (Turner & Engle, 1989). For each participant, each of 66 mathematical operations was randomly paired with one of 66 to-be-remembered words. During the task, participants were presented with sets of operation-word strings (e.g., IS (8/4) + 2 = 4 ? BIRD). Each participant was required to multiply or divide two integers and then add or subtract a third integer (e.g. (8/4) + 2 = 4). The integers ranged from 1 to 10. The participant was told to read the operation aloud, say "yes" or "no" at the question mark to indicate whether the number to the right of the equal sign was the correct answer, and then say the word aloud. Participants were instructed to remember the words for later recall. After the participant said the word, the experimenter immediately pressed a key and another operation-word string was presented. This process continued until a question mark cued the participant to write the to-be-remembered words from the set, in their exact order, on a response sheet. The number of operation-word strings per set varied from 2–6. Participants saw 3 presentations of each set size, and the presentation order of set sizes was randomized. The first 3 sets, each of length 2, served as practice. The span score was the total number of words recalled from correctly recalled sets. For example, if a participant correctly recalled all the sets containing 2 operations and one of the sets containing 3 operations, their span score would be 9 (2 + 2 + 2 + 3). All participants who fell below the cutoff of 85% accuracy on the yes/no responses were excluded from the experiments.

Design

The design for each experiment was a 2 (span group) × 2 (interference condition) between-subjects design. The two levels of span group were low and high span, based on performance in the operation span task. The two levels of interference condition were interference and noninterference, based on whether the pairs on each of the lists shared the same cue words or not (AB–AC–AB versus EF–CD–AB, interference and noninterference).

Materials

Participants learned 3 lists that each contained 12 pairs of words. Each pair was constructed from a compound word that was divided into a cue word and a response word. Because of the nature of compound words, list category was synonymous with cue word category because the response word in each pair often came from a different category than did the cue word, for example: bird–bath; eye–glass; dust–pan. All 12 cue words on a list shared the same semantic category (i.e., animals, body parts, natural elements). The compound words were chosen from those classified as a compound by Francis and Kucera (1982).

Cue words on all three lists in the interference condition were from the animals or body parts categories and the first and third lists were identical. The cue words and resultant

TABLE 1

Examples of Word Pairs That Were Learned on Each List for 4 Different Participants

	List 1	List 2	List 3
Non-Interference:			
Participant #1	dust–pan	bird–dawn	eye–glass
Participant #2	dust–pan	eye–tear	bird–bath
Interference:			
Participant #3	bird–bath	bird–dawn	bird–bath
Participant #4	eye–glass	eye–tear	eye–glass

list category were different for each of the 3 lists in the noninterference condition. Thus, the interference condition followed an AB–AC–AB paired-associate design, and the noninterference condition an EF–CD–AB paired-associate design. The first list in the noninterference condition always contained cue words from the natural elements category. The second and third lists in the noninterference condition contained cue words from the animals or body parts category. If a participant learned a second list with cue words from the animals category, they would then learn a third list from the body parts category.

Two categories were used in the interference condition so that each participant in the noninterference condition could provide a control for two different participants in the interference condition. This step was taken mainly to reduce the number of participants that would have been required for each experiment. Table 1 contains examples of word pairs on each of the three lists, which were learned by 4 different participants. For example, participant #1 in the noninterference condition might learn *bird–dawn* on the second list, and *eye–glass* on the third list. Bird–dawn on the second list would act as an interference control for participant #3 in the interference condition who learned 3 lists from the animals category. Eye–glass on the third list would act as a suppression control for participant #4 in the interference condition who learned 3 lists from the body parts category. We could then collapse across list category, providing that the list category factor did not interact with any other factors.

In the interference condition, one-half of the participants learned three lists containing cue words from the animals category, and the remaining half learned three lists containing cue words from the body parts category. One half of the participants in the noninterference condition learned a second list that contained cue words from the animals category and a third list with cue words from the body parts category. The remaining half learned the opposite, a second list containing cue words from the body parts category and a third list with cue words from the animals category.

Because the spoken response would activate a speech trigger in the computer, the response words on each list were matched on initial phoneme category, number of syllables, and frequency of occurrence in the English language. The matching was done in order to assure that any group differences in vocal response time in Experiment 2 would reflect retrieval time, rather than potential voicing differences. The average frequency of occurrence for each list ranged between 29 and 52 occurrences per million in the corpus of English usage (Francis & Kucera, 1982). Prior to the paired-associate learning phase on each list, participants completed a naming phase in which the response words were presented on the computer screen one at a time and participants read them aloud. The purpose of the naming phase was to determine whether any inherent group differences existed between participants in the interference and noninterference conditions to say each response word that were independent of any experimental manipulations.

Procedure

Paired-associate learning consisted of recalling a response word from a pair when presented with the cue word in the pair. The paired-associates task used a modified drop-out method, meaning that only the incorrect responses were retested. The task was programmed using the Micro Experimental Laboratory software (Schneider, 1988).

Instructions. There were some instructions that were common to both experiments. Participants in the interference and noninterference conditions were told that they would learn three lists each containing 12 word pairs. They were also told that there were 3 parts involved in learning each list: (1) naming each of the response words (2) studying each pair for 2 s, and (3) vocally recalling a response word when presented with the cue word. After naming each of the response words on List 2, participants in the interference condition were told that they would study the List 2 response words paired with the List 1 cue words. Participants in the noninterference condition were told that they would see new pairs on List 2. After completion of List 2 learning, and prior to List 3 learning, participants in the interference condition were told that they were going to learn the first list again. Hence, participants were always told what to expect in order to minimize any effect of surprise on the dependent measures.

Practice. The practice session was a short version of the actual paired-associates task in which participants learned a list of 5 digit-letter pairs. The practice was meant to acquaint participants with the three phases of learning each list.

Naming. In the naming phase of each list, a participant read each of the 12 response words when they appeared one at a time in the center of the computer screen. The response word remained on the screen until the participant's voice activated the voice key, at which time the response word disappeared and naming time was recorded. Participants controlled the presentation of each of the 12 response words by clicking a computer mouse.

Study. In the study phase of each list, each pair of words appeared in the center of the computer screen for 2 s. Participants were not required to make any response during this phase and were instructed to study each pair for the subsequent test phase. The study phase preceded the test phase on each of the three lists.

Test. Following the study phase, participants recalled each of the response words when presented with each of the cue words until they reached the initial criterion of 3 correct responses given to each cue word. A final test of each response was given upon reaching the initial criterion, which resulted in the final or total criterion of 4 correct responses given to each cue word. The final test was included so that all 12 responses would be equated on recency of retrieval before advancing to the next list. Each participant controlled stimulus presentation of each cue word in the test phase by placing the cursor in a box printed on the screen and clicking the left button of the mouse. The cue word appeared for up to 1350 ms in the first experiment and up to 32 s in the second experiment, or until the participant's vocal response triggered the voice key which made the word disappear. The time from presentation of the cue word until activation of the speech trigger was recorded by MEL. The cue–response pair was then printed to the screen for 2 s after each vocal response, irrespective of whether the response was correct or incorrect, in order to provide feedback and additional study time on each pair. Afterward, the experimenter coded the nature of the vocalized response which resulted in the box's being printed to the screen for the next cue word presentation. A modified dropout procedure was used where only incorrect responses were retested. The incorrect responses were retested in the order of original presentation.

EXPERIMENT 1

The first experiment was directed at whether a relationship exists between an individual's working memory capacity and their vulnerability to intrusions, as measured by number of intrusions and trials to reach criterion. Speed was stressed in the first experiment and a 1350 ms response deadline was used to encourage the vocalization of covert intrusions. Based on the findings of Rosen and Engle (1997), it was expected that the high span participants would show fewer intrusions and would require fewer trials to learn the second list. Further, if individuals in the interference condition produce more between- than within-list intrusions during second-list learning, then we can conclude that the interference was primarily due to response competition between the first- and second-list response items.

Method

Participants

One hundred and twenty students from the University of South Carolina participated in exchange for course credit. The participants were chosen for the low and high span groups based on their operation span score. Each was then randomly assigned to the interference or noninterference conditions. There were 30 participants in each of the noninterference groups (i.e., low and high span), 31 participants in the low span interference group, and 29 participants in the high span interference group. The mean operation span score was 7 for the low span participants and 26 for the high span participants.

Procedure

The general procedure was as described previously. Speed was stressed in the instructions for the first experiment and participants were told that the goal was to say the correct response before the deadline. However, they were told that if they felt unable to give the correct response before the deadline, then they should "say what is in your head even if you know it is the incorrect response." We gave these instructions because we found that participants in our pilot study would omit saying a response rather than say an incorrect response that had come to mind (i.e., intrusion). They were also told that if "nothing was in their head," then they should say nothing. Participants were allowed a maximum of 1350 ms to say the response from the onset of the cue word.

Nine types of responses were coded by the experimenter: correct responses that were made before the deadline, correct responses made after the deadline, between-list intrusions that shared the same cue word, between-list intrusions that did not share the same cue word, within-list intrusions, extra-experimental intrusions, saying the cue word instead of the response word from a list, the absence of a response, and random microphone errors.

Results

A 2 (span) × 2 (interference) × 3 (list) ANOVA conducted on the time to name each of the 12 responses on a list in the naming phase, showed little difference in naming time between the low and high span participants in the interference and noninterference conditions. This analysis indicated that there were no inherent group differences between the interference and noninterference conditions in the time to say each response word that were independent of any experimental manipulations. Also, a 2 (span) × 2 (category) ANOVA conducted on mean number of trials to reach criterion showed that there were no span differences in the number of trials to learn a list as a function of list category. Therefore, the data were collapsed across list category and a 2 (span) × 2 (interference) ANOVA design was used for the remaining analyses in this section.

Mean scores were calculated for each participant on the number of intrusions produced per trial, and the number of trials to reach criterion on each list, for the four conditions that resulted from crossing the two levels of span (low and high) with the two levels of interference (interference and noninterference). Mean number of trials to reach criterion included response omissions, whereas mean number of intrusions per trial did not, for obvious reasons. The method of treating outliers was the same in both experiments. Any vocal response times that were less than 300 ms or greater than 2.5 standard deviation units above the median within each cell were dropped. Outliers accounted for less than 1% of the data. An α level of .05 was used for all of the analyses.

The first experiment was directed at whether a relationship exists between an individual's working memory capacity and their vulnerability to intrusions. We predicted that the high span participants would show less interference from intrusions during second-list learning when compared to the low span participants. Figure 1 shows that the high span participants required fewer trials to reach criterion and produced fewer intrusions per trial on the second list, suggesting that they experienced less inter-

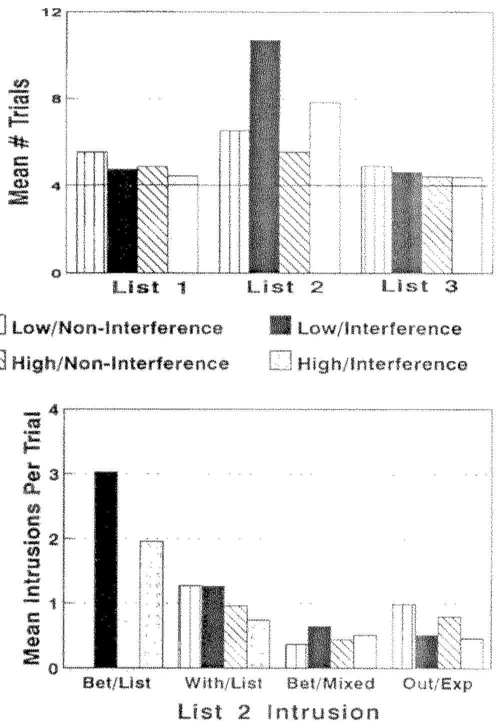

FIG. 1. Experiment 1 mean number of trials to reach criterion and mean number of intrusions per trial on List 2.

ference than did the low span participants. Also, second-list intrusion analyses showed that participants in the interference condition produced more than twice the number of between as within-list intrusions, suggesting that response competition between first- and second-list response items was the primary contributor to the interference that was experienced during second-list learning. Although we were primarily interested in number of intrusions and trials to reach criterion on List 2, we also examined vocal response time and percent correct recall on List 2 for evidence of interference. Unfortunately, because we used a response deadline to encourage the vocalization of covert intrusions, both the low and high span participants showed a low level of recall accuracy on Trial 1 of the second list. More importantly, the low span participants were significantly less accurate than were the high span participants on Trial 1, which precludes us from interpreting and discussing the response time data on List 2. Consequently, the analyses that were conducted on vocal response time and percent correct recall are not reported.

Number of trials to learn List 2. There were main effects of span, $F(1,116) = 15.27$, $p < .001$, $MS_e = 7.35$ (mean of 8.64 versus 6.65 trials, low and high span) and interference, $F(1,116) = 43.04$, $p < .0001$, $MS_e = 7.35$ (mean of 9.31 versus 6.06 trials, interference and noninterference), showing that the high span participants and the participants in the noninterference condition required fewer trials to reach criterion on the second list. Recall that 4 correct responses was the criterion of learning on each list, as represented by the horizontal line in the top graph of Fig. 1. A closer examination of this graph reveals that participants in the interference condition required twice the number of trials to learn the second list as the other two lists.

A significant span X interference interaction in the number of trials to reach criterion on List 2 showed that the high span participants experienced less interference than did the low span participants, $F(1,116) = 3.63$, $p = .05$, $MS_e = 7.35$. Simple main effect comparisons showed that both the low span participants, $F(1,59) = 24.88$, $p < .0001$, $MS_e = 10.76$ (mean of 10.70 versus 6.51 trials interference and noninterference) and the high span participants in the interference condition, $F(1,58) = 20.54$, $p < .0001$, $MS_e = 3.81$ (mean of 7.82 versus 5.52 trials, interference and noninterference) required more trials to reach criterion on the second list when compared to their control. Although both groups showed interference, the high span participants showed significantly less interference.

Number of intrusions per trial on List 2. There were main effects of span, $F(1,114) = 15.66$, $p < .0001$, $MS_e = 3.49$ (mean of 5.50 versus 4.14 intrusions, low and high span) and interference, $F(1,114) = 52.74$, $p < .0001$, $MS_e = 3.49$ (mean of 6.07 versus 3.57 intrusions, interference and noninterference), showing that the high span participants and the participants in the noninterference conditions produced fewer intrusions per trial on the second list. There was no span X interference interaction.

Type of intrusion on List 2. The bottom graph in Fig. 1 illustrates the four types of intrusions that were included in these analyses: between-list intrusions from pairs that shared the same cue word (between-list), between-list intrusions from pairs that did not share the same cue word (between/mixed), within-list intrusions, and outside experimental intrusions. Omissions were excluded from the analyses because there were too few to analyze. A comparison of between- and within-list intrusions showed that both low and high span participants produced over twice as many between- as within-list intrusions on List 2. This finding suggested that response competition between first and second-list response items was the primary contributor to interference during second-list learning. There were few between-list intrusions produced where the two responses did not share the same cue word (i.e., between/mixed). There was a main effect of type of intrusion produced by the low span participants, $F(1,60) = 34.79, p < .0001, MS_e = 1.37$ (mean of 3.03 versus 1.27 intrusions per trial, low span between- and within-list) and the high span participants, $F(1,53) = 24.13, p < .0001, MS_e = .84$ (mean of 1.96 versus .74 intrusions per trial, high span between- and within-list). Similarly, a comparison of mean intrusions per trial on the second list showed that the high span participants produced fewer between-list, $F(1,57) = 8.57, p < .01, MS_e = 1.96$ (mean of 3.03 versus 1.96 intrusions per trial, low and high span) and within-list intrusions, $F(1,56) = 15.17, p < .001, MS_e = .26$ (mean of 1.27 versus .74 intrusions per trial, low and high span) than did the low span participants. This suggested that the high span participants experienced less interference than did the low span participants. There were no differences found in the number of between/mixed intrusions produced on the second list. Finally, both the low and high span participants in the noninterference condition produced more outside experimental intrusions on List 2, $F(1,75) = 5.57, p < .05, MS_e = .56$ (mean of .89 versus .48 intrusions per trial, noninterference and interference conditions).

Although we were primarily interested in performance on the second list, we also examined the number of trials to reach criterion and the number of intrusions produced per trial on the third list. We are reporting the intrusion findings from the third list because they will become important later in providing insights into List 3 response times in Experiment 2.

Number of trials to learn List 3. Planned comparisons that were conducted on the mean number of trials to reach criterion on the third list showed a main effect of span, $F(1,116) = 12.66, p < .001, MS_e = .29$. The high span participants required fewer trials to reach criterion on the third list compared to the low span participants (mean of 4.76 versus 4.41 trials, low and high span).

Number of intrusions per trial on List 3. Planned comparisons that were conducted on the mean number of intrusions produced per trial on the third list, irrespective of type of intrusion, showed a main effect of span, $F(1,114) = 11.24, p < .01, MS_e = 1.09$. The high span participants produced fewer intrusions per trial than did the low span participants on the third list (mean of 1.82 versus 1.15 intrusions per trial, low and high span).

Type of intrusion on List 3. There were no span differences found in the type of intrusion made on the third list. The most common types of intrusion made on the third list were between- and within-list intrusions (mean of .9 versus .56 between-list intrusions per trial, low and high span; mean of .84 versus .51 within-list intrusions per trial, low and high span).

Discussion

The question that motivated the first experiment was whether a relationship exists between an individual's working memory capacity and their vulnerability to intrusions. The results suggested that this relationship does exist because the high span participants experienced fewer intrusions and required fewer trials to reach criterion on the second list than did the low span participants. The combination of the speed instructions and the 1350 ms deadline was successful in causing the participants to vocalize first-list intrusions during second-list learning. Also, the 2:1 ratio of between- to within-list intrusions indicated that our combination of compound word pairs and overlearning caused the first-list response items to come to mind first, when presented with second-list cue words that were identical to the first-list cue words. Further, the 2:1 ratio indicated that incorrect responses reflected intruding first-list response items. It could be argued that the reason for the span differences in intrusions is that the high span participants learned the first list as compound nouns rather than as pairs, so experienced less interference from first-list response items when learning the second list. However, the low and high span participants showed the same 2:1 ratio of between- to within-list intrusions, suggesting that the two groups did not differ in first-list learning strategies. More importantly, the high span participants produced significantly fewer intrusions overall than did the low span participants. We now examine the relationship between working memory capacity and suppression of intrusions.

EXPERIMENT 2

The findings of the first experiment suggested that a relationship exists between an individual's working memory capacity and their vulnerability to intrusions. The second experiment was directed at whether a relationship also exists between an individual's working memory capacity and their ability to suppress intrusions. The first experiment used speed instructions and a response deadline to encourage the vocalization of covert intrusions. In contrast, the instructions in the second experiment emphasized accuracy and participants were allowed a maximum of 32 s to make each response. We expected that 32 s would give participants sufficient time to monitor for first-list intrusions during the learning of the second list and to suppress them. Consequently, we were most interested in examining the vocal response times on the first trial of the third list for evidence of suppressed first-list response items that had intruded during the learning of List 2. We expected that the high span participants would be better able to suppress the intruding first-list response items during second-list learning and so would show slower response times on the first trial of the third list compared to a high span control group who was learning the same third list for the very first time. We were also interested in a within-subject comparison of the time to retrieve the response items on List 3. If high span participants suppressed the response items from List 1 during the learning of List 2, then they should be slower to retrieve the List 1 response items during the relearning of the first list (i.e., List 3) than they were when they first learned List 1.

Method

Participants

One hundred and twenty students from the University of South Carolina participated in exchange for course credit. The participants were chosen for the low and high span groups based on their operation span score. Each was then randomly assigned to the interference or noninterference conditions. There were 30 participants in each of the resulting 4 groups (i.e., low span interference and noninterference, high span interference and noninterference). The mean operation span score was 7 for the low span and 26 for the high span participants.

Procedure

The general procedure was described previously. Accuracy was stressed in the second experiment and participants were instructed to "really try hard to come up with the correct response." The primary measures of interest were the time to make a vocal response from the onset of the cue word and mean percent correct recall. Six types of response were coded by the experimenter: correct responses, between-list intrusions, within-list intrusions, extra-experimental intrusions, the omission of a response, and random microphone errors.

Results

A 2 (span) × 2 (interference) × 3 (list) ANOVA conducted on the time to name each of the 12 responses on a list in the naming phase showed little difference in naming time between the low and high span participants in the interference and noninterference conditions. This finding indicated that there were no inherent group differences between the interference and

TABLE 2

Trial 1 Mean Vocal Response Times in Experiment 2

	Trial 1 Mean Vocal RT			
	List 1	List 2	List 3	
Low span:				Mean
Non-Interference	1546.09	1882.84	1294.27	1574.40
Interference	1135.74	2119.91	1188.08	1481.24
Mean	1340.91	2001.37	1241.17	
High span:				Mean
Non-Interference	1229.50	1468.82	1120.28	1272.87
Interference	1077.41	2031.62	1234.57	1447.87
Mean	1153.45	1750.22	1177.42	

noninterference conditions in the time to say a response word, independent of any experimental manipulations. Also, a 2 (span) × 2 (category) ANOVA conducted on mean vocal response time showed that there were no span differences found as a function of list category. Therefore, the data were collapsed across list category and a 2 (span) × 2 (interference) ANOVA design was used for the remaining analyses in this section.

Recall that the first phase of learning each list was to name each of the response words. Therefore, what we refer to as "Trial 1" in the analyses followed the naming phase and was the first attempt for participants to recall the response word when presented with the cue word during the test phase. The mean vocal response time for Trial 1 included only the latencies for correct responses. Table 2 contains the mean vocal response times for Trial 1 on each of the three lists for the four conditions that resulted from crossing the two levels of span (low and high) with the two levels of interference (interference and noninterference). The method of treating outliers, which constituted 2.5% of the data, was the same as in the first experiment. An α level of .05 was used for all of the analyses.

The second experiment was directed at whether a relationship exists between an individual's working memory capacity and their ability to suppress intrusions. Based on the Rosen and Engle (1997) findings, we expected that the high span participants would be better able to suppress the intruding first-list response items during the learning of List 2. Consequently, we were most interested in whether high span participants in the interference condition would show slower retrieval times on the first trial of relearning the first list (i.e., List 3), when compared to a control group who was learning the same list for the very first time.

The top graph in Fig. 2 shows that the high span participants in the interference condition were slower than their control on the first trial of List 3. In addition, the bottom graph in Fig. 2 shows that the high span participants were slower on the first trial of relearning List 1 when compared to themselves when they first learned List 1. Both of these findings suggested that the high span participants had suppressed first-list response items during second-list learning. In

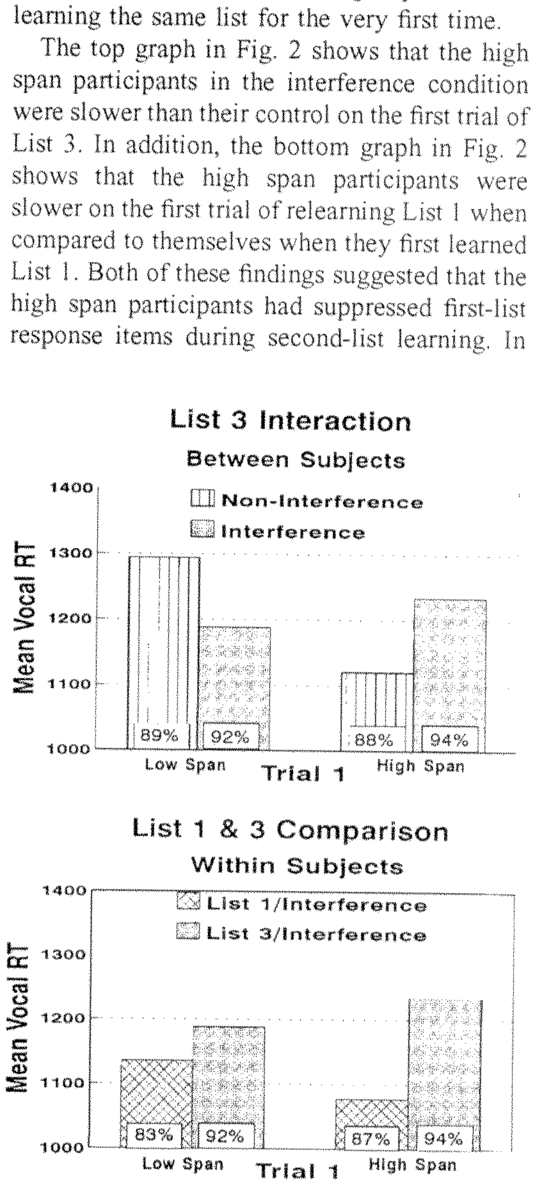

FIG. 2. Experiment 2 between subject comparison of mean vocal response times on Trial 1 of List 3, and within subject comparison of mean vocal response times on trial 1 of Lists 1 and 3.

contrast, the low span participants did not show any evidence for suppression. Instead, the low span participants in the interference condition showed faster response times than did their counterparts in the control condition on Trial 1 of the third list, suggesting that they experienced facilitation of first-list response items.

List 3 response time. There was a significant span × interference interaction on Trial 1 of the third list, $F(1,116) = 7.83$, $p < .01$, $MS_e =$ 46,540.43. Simple main effect comparisons showed that the high span participants in the interference condition were 114 ms slower than their control, $F(1,58) = 3.89$, $p = .05$, $MS_e =$ 50,398.85, whereas the low span participants in the interference condition were 106 ms faster than their control, $F(1,58) = 3.96$, $p = .05$, MS_e = 42,682.01. Also, within subject comparisons of Trial 1 response times on the first and third lists, in the interference condition, showed a main effect of list, $F(1,58) = 16.45$, $p < .001$, $MS_e =$ 20,013.52; and a span × list interaction, $F(1,58) = 4.12$, $p < .05$, $MS_e =$ 20,013.52. Simple main effect comparisons showed that the high span participants were 157 ms slower to retrieve response items on Trial 1 of the third list than they were to retrieve the same response items on List 1, $F(1,58) = 7.94$, $p < .01$, $MS_e =$ 46,661.34. In contrast, the low span participants showed little difference in mean vocal response times on Trial 1 of the first and third lists, $F(1,58) = 1.27$ $p < .3$, $MS_e =$ 32,452.90. These findings provide strong evidence that the high span participants in the interference condition suppressed first-list response items during second-list learning, whereas the low span participants in the interference condition did not.

List 3 percent correct recall. Planned comparisons of percent correct recall on Trial 1 of the third list showed that participants in the interference conditions were more accurate than their controls, $F(1,116) = 7.33$, $p < .01$, $MS_e =$ .008. No main effects nor interactions involving span were significant.

Although we were primarily interested in the response times on the first trial of the third list, we also examined response times and percent correct recall on List 2 for evidence of first-list interference. The high span participants in the interference condition appeared to experience a larger effect of first-list interference when compared to their low span counterparts, yet the low span participants were slower overall on the first trial of the second list. More importantly, the low span participants were significantly less accurate than the high span participants on the first trial of the second list, which precludes us from interpreting and discussing the response time data from List 2. Consequently, the List 2 analyses are not reported.

Discussion

The second experiment examined whether a relationship exists between an individual's working memory capacity and their ability to suppress intrusions. The instructions emphasized accuracy and so focused on speed of retrieval or vocal response time as a primary measure of suppression. There were two important findings from the second experiment. First, a relationship does exist between an individual's working memory capacity and their ability to suppress intruding first-list response items. The high span participants in the interference condition were 114 ms *slower* than their control to retrieve first-list response items on Trial 1 of the third list, whereas the low span participants were 106 ms *faster* than their control. Second, the high span participants in the interference condition were 157 ms *slower* to retrieve first-list response items on Trial 1 of the third list, compared to when they first retrieved the same response items on Trial 1 of the first list. In contrast, the low span participants in the interference condition showed little difference in the vocal response times between the first and third lists. Both of these findings suggested that the high span participants in the interference condition had suppressed first-list response items during second-list learning, whereas the low span participants had not. We would also like to mention that had we only examined the retention of first-list response items (i.e., number of correctly recalled items), as paired-associate studies typically do, then we would have mistakenly concluded that suppression had not occurred for the high span participants.

An alternative explanation for the high span participants' slower response times on the first trial of the third list is that the slower times reflected increased response competition between the second and third list response items because the second list was better learned, and more highly activated, for the high span participants. However, there are two findings that refute this argument. The first finding is that there were no span differences found in the number of trials to reach criterion on the second or third lists for participants in the interference condition. This finding suggests that the low and high span participants had reached a comparable level of learning, and activation, on the second list. Further, both the high and low span participants produced few List 2 intrusions during the learning of List 3. Across all List 3 trials, there was an average of only .32 intrusions for the low span participants and .36 for the high span participants, suggesting that the high span participants did not experience more response competition from second-list response items than did the low span participants. In fact, a similar pattern of results was seen in the List 3 intrusion findings from Experiment 1, when overt intrusions were actually encouraged. The second finding was that both the low and high span participants in the interference condition showed an accuracy rate in excess of 90% (92% for the low span participants and 94% for the high span participants). These findings do not support an argument that List 2 response items were better learned or more highly activated for the high span participants. It is more likely that the slower response times for the high span participants on Trial 1 of the third list reflected the suppression of first-list response items.

It could also be argued that the critical interaction on the first trial of the third list, which supports an interpretation of suppression, occurred because the performance of the low span participants in the control condition was atypical. Further, if the low and high span participants in the control condition had behaved the same (i.e., comparable response times), then the low span participants in the interference condition would have showed suppression like their high span counterparts. There are three findings that render this argument untenable. First, when we compare the times for the low and high span participants in the control condition to say each response item on List 3, before any cued recall occurred (i.e., test phase), we find that they were essentially the same (mean of 827.57 ms versus 835.96 ms, low and high span participants). This finding shows that there were no inherent group differences between the low and high span participants in the control condition that might have affected vocal response time. Second, when we compare accuracy rates on the first trial of the third list, we find that the low and high span participants in the control condition showed comparable accuracy rates (mean of 89 versus 88% correct, low and high span participants). Third, both the low and high span participants showed a "learning to learn" effect, or practice effect, that is typically found in list-learning experiments. In fact, the low span participants in the control condition showed more than twice the learning to learn effect across lists than their high span counterparts showed (mean of 252 ms versus 109 ms reduction in response times from List 1 to List 3, low and high span participants). In spite of these three findings, the low span participants in the control condition were still 174 ms slower than their high span counterparts when they were required to provide a response word when presented with a cue word. Recall that these studies were directed at examining individual differences in behavior. Therefore, it may not make sense to expect the low and high span participants in the control condition to behave exactly the same. It may be that low span participants experience more "general" interference, that is unrelated to the experimental procedure or stimuli, when compared to the high span participants. We will discuss the nature of our suppression findings in the general discussion section.

GENERAL DISCUSSION

These studies were motivated by two questions. The first question asked whether individuals who differ in central executive or working memory capacity show a corresponding difference in the number of intrusive thoughts and behaviors they experience. The second question asked whether a relationship also exists between an individual's working memory capacity and their ability to suppress those intrusive thoughts.

In the first experiment, span differences were found in the number of trials to reach criterion and the number of intrusions produced per trial on the second list, suggesting that working memory capacity does play a role in an individual's vulnerability to intrusions. The high span participants required fewer trials to reach criterion and produced fewer intrusions (i.e., between- and within-list) than did the low span participants. These findings suggested that the high span participants experienced less interference from intrusions during second-list learning when compared to the low span participants.

Our second question asked whether individuals who differ in working memory capacity will show a corresponding difference in the ability to suppress intrusions. An examination of the vocal response times on the first trial of the third list in Experiment 2 showed that the high span participants in the interference condition were 114 ms *slower* than their control, whereas the low span participants in the interference condition were 106 ms *faster* than their control. In addition, the high span participants in the interference condition were 157 ms *slower* to retrieve first-list response items on the third list compared to when they first retrieved the very same response items on the first list. Both of these findings strongly support the conclusion that the high span participants had suppressed intruding first-list response items during second-list learning, whereas the low span participants did not.

A Four Component Model of Retrieval

The present set of experiments was motivated from a set of four category fluency experiments (Rosen & Engle, 1997), where the findings were explained within the context of a retrieval model that was based on individual differences in working memory capacity. The model consists of one component that does not demand controlled attention, namely, automatic spreading activation, and three components that do require controlled attention: covert monitoring for potential errors, suppression of previously retrieved information, and controlled search.

The findings from the present set of studies fit well with the idea that there are four components involved in retrieval in the paired-associates task and probably other retrieval tasks as well (Rosen & Engle, 1997). The first component is automatic spreading activation that results from the presentation of a cue. No span differences would be expected for this component. Automatic spreading activation was probably most important in eliciting the well-learned response item of the compound word pairs at the end of List 1 learning and early into List 2 learning. The first-list response item, retrieved automatically as a correct response at the end of List 1 learning, would then become an intrusion when retrieved automatically at the beginning of List 2 learning. The remaining retrieval components of the Rosen and Engle model require controlled attention.

The second of the four retrieval components is covert monitoring for potential errors resulting from automatic spreading activation. When this component fails, it would lead to overt intrusions such as the List 1 intrusions that were made during the learning of List 2 in the first experiment. This component was made particularly important by the effect of automatic activation of the previously learned, but now incorrect, response. Monitoring would be important in order to make sure that the incorrect response is not vocalized and would become more important with the addition of accuracy instructions and oral recall. This component requires sufficient time to occur because it is a controlled process. When participants are pushed to respond quickly while reducing the importance of accuracy, this component may not be implemented. In the first experiment, in which the participants were given a response deadline, more intrusions were produced by both the low and high span participants in the interference conditions during the learning of the second list. The intrusions most likely occurred because the response deadline gave participants little time to covertly monitor for intrusions. Unlike the first experiment, few intrusions were produced in the second experiment because there was sufficient time for both the low and high span participants to covertly monitor for intrusions. Participants were allowed up to 32 s to make a response and therefore had time to covertly identify and prevent the vocalization of a covert intrusion, should it occur.

The third retrieval component is the selective suppression of retrieved information resulting from automatic spreading activation. It was expected that the high span participants would be better able to suppress intruding response items when compared to the low span participants. In fact, in the second experiment, the high span participants showed evidence for suppression of first-list response items, whereas the low span participants did not. The high span participants in the interference condition were slower to retrieve first-list response items on Trial 1 of the third list when compared to their control. Further, the naming times on these first-list response items did not show evidence of suppression, suggesting that the suppression that was later found in the vocal response times did not occur at the level of access, word form, or production. It was only when retrieval was associated with a cue (i.e., during the test) that we found evidence for suppression. Consequently, it may be that the high span participants suppressed the link between the cue and response word in each of the first-list pairs, during second-list learning, in order to facilitate the formation of new associations between the new second-list response words and the old first-list cue words. However, we can only speculate about the nature of the suppression that was found for the high span participants in the second experiment.

Rosen and Engle (1997) argued that the low span participants in their fluency studies performed worse than did the high span participants because they did not have the working memory capacity needed to monitor their output while concurrently suppressing previously retrieved items or searching for new items. Similarly, when accuracy was stressed in the present set of experiments (Experiment 2), the low span participants may have been unable to both suppress intrusions and monitor their output in order to maintain accuracy, like the high span participants. Although the low span participants did not show suppression, they were still able to successfully monitor their output and so produced few intrusions when given accuracy instructions. One explanation for the lack of suppression is that the low span participants were unable to allocate controlled attention to more than one component of the task at a time. This explanation is compatible with recent theories that view controlled attention, or central executive function, as multicomponent in nature (Baddeley & Della Sala, 1996; Baddeley, Della Sala, Papagno, & Spinnler, 1997). However, there is always the possibility that low span participants are unable to suppress, regardless of how many other components of a task require controlled attention. Although we might entertain the idea of a multicomponent central executive, we maintain that central executive function is "fueled" by a single pool of attentional resources.

The fourth and final component of the retrieval model is controlled search for the correct response after the presentation of a cue word. This component would be necessary during those times when the correct response does not come quickly to mind. Therefore, this component requires controlled attention and sufficient time to occur. Based on the category fluency findings of Rosen and Engle (1997), it would be expected that the high span participants would also be better at searching for the correct response when given sufficient time. However, these studies were not directed at controlled search and so we have no way to determine whether span differences existed in controlled search from the present set of data.

Central Executive and Frontal Lobe Functioning

In the introduction to this paper, we discussed the relationship between resistance to interference and suppression. We based an argument for span differences in suppression on Dempster's (1991, 1992) view that the ability to resist interference may be an important source of individual and developmental differences, and, more importantly, that a relationship exists between resistance to interference and frontal lobe functioning. Frontal lobe functioning is commonly assessed through tasks such as the Wisconsin card sorting task and verbal fluency tasks. However, the paired-associate task has also shown sensitivity to frontal lobe functioning. Shimamura et al. (1995) found that frontal lobe patients showed a greater vulnerability to interference in a paired-associate task when compared to normals. Also, Uhl et al. (1990) found evidence for frontal lobe activity in normals at a point during paired-associate learning when they would have been resisting interference (i.e., during second-list learning). How, then, do resistance to interference, frontal lobe functioning, and working memory capacity relate to each other?

We have come to believe that the construct that we have labeled working memory capacity is simply another name for individual differences in central executive functioning (see Rosen & Engle, 1997, and Engle & Oransky, in press). Recall that the central executive is the attentional component of Baddeley's (1986) working memory model. There are models of the central executive as frontal lobe function (Baddeley & Della Sala, 1996; Baddeley et al., 1997; Baddeley & Wilson, 1988), as well as models of controlled attention as frontal lobe function (Norman & Shallice, 1986; Posner & Peterson, 1990). Although no models exist yet of working memory capacity as frontal lobe/central executive function, our model of retrieval is one step in this direction. However, further research needs to be conducted on the relationship between working memory capacity and other processes commonly associated with frontal lobe functioning, such as planning and task switching, before we can develop a more complete model of working memory capacity as frontal lobe/central executive function. Until then, we can only hypothesize about this relationship, based on what we already know about the role of working memory capacity in performance on tasks that are designed to assess frontal lobe function.

Rosen and Engle (1997) found that a relationship existed between working memory capacity and performance in a fluency task. Also, the current set of studies found a relationship between working memory capacity and suppression (i.e., resistance to interference) during paired-associate learning. As mentioned earlier, both fluency and paired-associate tasks are sensitive to frontal lobe functioning. If these tasks are sensitive to both working memory capacity and frontal lobe functioning, then it seems only a short step to suggest that a relationship exists between working memory capacity and frontal lobe functioning. Further, Engle and colleagues (Engle, Tuholski, Laughlin, & Conway, in press) have recently found a relationship between measures of working memory capacity, and measures of "g," or general intelligence, that have been linked to frontal lobe function (Duncan, Emslie, & Williams, 1996). We understand that in arguing for a relationship between working memory capacity and frontal lobe function, we are comparing the performance of low span individuals with frontal lobe patients. However, we believe that the basis of the relationship is that both groups share a deficit in controlled attention. In the present set of studies, a deficit in controlled attention may have influenced whether an individual was able to suppress or resist interference while engaged in other components of the task. Although both the low and high span participants successfully monitored their output, only the high span participants showed that they were able to both monitor their output and suppress intrusions. If a relationship truly exists between working memory capacity and frontal lobe functioning, then the ability to suppress intruding thoughts and behaviors may be one link in this relationship.

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