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The Deployment of Attention in Short-term Memory Tasks: Tradeoffs between Immediate and Delayed Deployment

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Abstract

Memory at times depends on attention, as when attention is used to encode incoming, serial verbal information. When encoding and rehearsal are difficult or when attention is divided during the list presentation, more attention is needed in the time following the presentation and just preceding the response. Across 12 experimental conditions observed in several experiments, we demonstrated this by introducing a nonverbal task with three levels of effort (no task, a natural nonverbal task, or an unnatural version of the task) during a brief retention interval in a short-term digit recall task. Interference from the task during the retention interval was greater when other factors drew resources away from the encoding of the stimuli, including unpredictability of the end point of the list, rapid presentation, and a secondary task during the list presentation. When those conditions complicate encoding of the list, we argue, attention is needed after the list to retrieve the contents of passive memory (i.e., post-categorical phonological storage and/or precategorical sensory memory) to the focus of attention for recall.

Although attention is a critical concept in cognitive psychology, it has always been a complex one, with different connotations for different researchers. We take it to mean a central, limited-capacity resource that can be voluntarily applied to both processing, or manipulation, of stored information and temporary memory storage itself (cf. Baddeley & Hitch, 1974; Cowan, 2005a, 2005b; Engle, Kane, & Tuholski, 1999; Kane et al., 2004). The *central* aspect indicates that the resource is shared between all modalities (vision, hearing, etc.) and types of coding (phonological, orthographic, spatial, etc.). The *limited-capacity* aspect indicates that one type of storage or processing can be increased only at the expense of other types. The allocation of attention can be modified voluntarily, as is indicated when participants modify their allocation according to variable instructions or payoffs. (This does not imply that attention is completely voluntary; for example, a thunderclap can recruit attention away from an assigned task momentarily.)

The most difficult aspect of attention is that not all processes fall in its domain; some types of process, notably very-well-learned ones, are impervious to the allocation of attention (Shiffrin, 1988). Also, task tradeoffs that are not central in nature are not considered to demonstrate attention. For instance, if performance in a listening task trades off with a reading task but not

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with a maze-navigation task, whereas performance in a picture-matching task trades off with maze navigation but not reading, the tradeoffs are said to result from linguistic and spatial processing interference, respectively; not from limited attention.

Our thesis is that there is a domain-general, limited attentional resource for which storage and processing compete. Perhaps to simplify the theoretical role of attention, several theorists have proposed that attention is used for processing and perhaps for some memory-maintenance activities, but not for memory storage itself, which is considered passive or automatic once the information has been suitably encoded (Baddeley, 2007, 1986; Baddeley & Logie, 1999). However, this simplification makes it difficult to explain some tradeoffs, such as some of those demonstrated by Baddeley and Hitch (1974), and is in need of further study. If it can be shown that attention is needed to convert information to a form in which it can be recalled, that will be a first step in demonstrating that attention is used for storage.

At least two theoretical analyses of working memory suggest that attention should be needed for storage. First, according to suggestions of Cowan (1988, 1995, 2001), a limited amount of information can be held in the focus of attention (on average, 3 to 5 meaningful chunks), and deliberate responses require that the information be transferred there rather than remaining in the activated portion of long-term memory outside of attention. (For a slightly different version of this type of view see Oberauer, 2005.) According to this view, also, the limit in processing occurs because only a limited number of chunks of information can be held in the focus of attention and these chunks sometimes must include the task goals and instructions (especially when conflicting responses are activated, as in Kane & Engle, 2003), which then would be expected to compete with the data being stored in the focus of attention. That expected competition between processing and storage was examined by Daneman and Carpenter (1980) and by Turner and Engle (1989), but not in a way that pits verbal storage against non-verbal processing as in the present study. Second, according to Baddeley (2007,2000), abstract information (neither purely phonological nor purely visuospatial in nature) can be held in a newly-noted, capacity-limited component of working memory termed the *episodic buffer* Baddeley suggested that attention may be needed for storage in this buffer, unlike his assumptions (Baddeley, 1986) for phonological and visuospatial storage. Also, presumably, attention is needed to carry out processing in the case of stimulus-response incompatibility, so this too could suggest a tradeoff between our two tasks (verbal storage and nonverbal processing).

To help evaluate these possibilities, we describe a speeded task procedure that was used to assess the role of attention during a brief retention interval in running and fixed-length short-term recall tasks. A tradeoff between two tasks (on one hand, the transfer of auditory-verbal information to a retrievable form and, on the other hand, a speeded visual-spatial response task with two levels of stimulus-response compatibility) would be evidence of competition between processing and storage for a shared attentional resource.

The Speeded, Intervening Task Procedure

The speeded task interposed between memory stimuli and memory response was a manual-response analogue of the prosaccade / antisaccade task (Hallet, 1978) in which an individual is to look toward a target (prosaccade condition) or, with more difficulty, away from the target (antisaccade condition). The speeded task was interpolated between the presentation and recall phases of short-term recall. To avoid the problem of confounding effects from shared specific processes, we used two versions of the speeded task that are physically identical, but differ in the demand for attention (a research strategy used previously by Watkins, Watkins, Craik, & Mazuryk, 1973). Moreover, the speeded task and the short-term recall tasks do not seem to share modality or other specific processes.

An eye-tracking instrument is typically used to measure gaze direction and duration, but some (Friedman & Miyake, 2004b; Roberts, Hager, & Heron, 1994) have devised manual key press and reaction time experiments to infer when participants make a prosaccade response in an antisaccade condition. Likewise, in our speeded task, a centered fixation point and then a box appeared on either side of the display. Participants made a manual key-press response that corresponded either to the same side of the screen (less demanding) or the opposite side (more demanding). We shall refer to these as the pro-press and anti-press responses, respectively. The speeded task procedure used in these experiments is illustrated in Figure 1. We predicted that responding in the anti-press condition in our speeded task would require more attention than responding in the pro-press condition, thereby creating a conflict when attention is needed to extract information from sensory memory or for retrieval of information into the focus of attention. The pro-press condition is likely to demand some attention (because of the need to respond), though not as much as the anti-press condition.

Memory-Task-Dependent Expectations

The principal analyses will focus on the effects of the speeded task on short-term recall tasks designed to prevent active updating and rehearsal during the presentation of the memoranda. They were running memory span with a rapid presentation rate (Experiment 1a) and ordinary list recall with the added requirement of articulatory suppression (Experiment 2a). Encoding during presentation of the memoranda is difficult under these task conditions for different reasons. Several methodological properties of the running span task differentiate it from typical fixed list or simple span tasks. Running span presents an unpredictable number of items in sequence and requires recall from the end of the list (Pollack, Johnson, & Knaff, 1959). For example, we presented 12 to 20 spoken digits at random, and the task was to recall the final 6 digits. A common assumption about running span procedures is that they involve an active process of continually updating a working-memory register and holding just the final few items. Although this might be feasible if the items are presented slowly, the items in our version of running span are presented quickly so as to minimize the opportunity for rehearsal (see Bunting, Cowan, & Saults, 2006; Hockey, 1973). Thus, the rapid rate of presentation, together with the unpredictable list length, makes covert rehearsal or active processing of the items extremely unlikely, or at least unhelpful.

In an ordinary span task, such as the fixed-length list task in Experiments 2a–2c, articulatory suppression, rather than unpredictability and a rapid presentation rate, prevents rehearsal (Baddeley, 1986). Articulatory suppression may not interfere with encoding but at least prevents subvocal rehearsal. Baddeley (2007) has argued that items presented auditorily, as were the items in all of our experiments, gain automatic access to the phonological loop. However, articulatory suppression prevents subvocal rehearsal, as indicated by the fact that the word length effect is not obtained under such conditions. Furthermore, Cowan, Cartwright, Winterowd, and Sherk (1987) found that even when items are acoustic, an articulatory code is not completely used automatically under articuatory suppression conditions, as evidenced by a much-reduced phonological similarity effect.

We thus feel confident that what is vulnerable to distraction in running span at the rapid presentation rate or ordinary list span with articulatory suppression is, if anything, the process of extracting information from a passively-held form of storage into an active, capacity-limited holding mechanism, such as the focus of attention (Cowan, 2001) or episodic buffer (Baddeley, 2000). We remain agnostic as to how the memoranda are maintained prior to recall. Cowan (1984, 1988) suggested there are two forms of passive storage: a brief, precategorical echoic trace and a more processed, though passively maintained, phonological store. Subjects almost certainly rely on both.

We expect that attention supplements passive storage and encoding from sensory memory when active maintenance rehearsal is difficult or impossible, and we submit that this is the case in running span at a rapid presentation rate (Experiment 1a) or in ordinary list span with articulatory suppression (Experiment 2a). Encoding during item presentation is, under these circumstances, weak in semantic or lexical elements and predominantly includes passively-held components such as sensory memory. Thus, we argue that if less attention is available during the list presentation, then more attention is needed in the time following the presentation and just preceding the response to extract information from passive storage to more meaningful units that can be used in the response. Our primary analyses will focus on the effects of the speeded task during the retention interval on these span tasks.

General Method

Participants

All participants spoke English as a first language, had normal or corrected-to-normal vision, and had normal use of their dominant writing hand, which was used to type responses. All of the experiments were conducted at the University of Missouri except Experiment 1c, which was conducted at the University of Illinois at Chicago. All participants were recruited from undergraduate psychology subject pools and participated as part of their coursework in introductory psychology. Each participant took part in just one experiment.

Tasks and Materials

Memory Tasks—Participants listened to lists of digits (the numbers 1 – 9) and recalled the last six. In the *running memory span task* (Experiments 1a– Experiments 1d), the digit lists contained 12 – 20 randomized digits and ended unpredictably. List length was also randomized but each list length from 12 – 20 digits was sampled equally often. As a restriction on digit randomization, repetitions of the same digit were permitted only after five or more intervening digits. In the *ordinary memory span task* (Experiments 2a–2c), the length of the digit lists was predictably fixed at six random, non-repeating digits per list. In both tasks, each digit was used approximately equally often

The memoranda were always spoken digits, which were recorded in a male voice and digitally compressed to play within 250 ms each; though speeded, they remained easily identifiable. When recall was prompted, participants recalled the digits by typing them on a keypad. Participants pressed [Enter] to advance to the next line after typing a digit or to leave a line blank. Use of the backspace key to edit the current line was permitted, but editing prior entries was not. The digit presentation rate, which was always constant within an experiment, was either fast (4 digits/s) or slow (1 digit/s). The same compressed digits were used in every experiment but silent periods were introduced between digits to make the presentation rate 1 digit/s.

Dual Tasks—Participants listened to the digits while performing articulatory suppression (saying “the”), while knee tapping with their non-dominant hand, or while doing nothing (the dual-task control condition). The articulation/tapping rate was approximately 2 responses/s and was practiced before being used in the list memory task. Participants discontinued articulatory suppression or knee tapping during digit recall.

Speeded[1] Interpolated Task—This was a visual computerized task requiring a key-press response. The visual stimulus was a 3” × 6”, vertically-oriented rectangle that contained six horizontal lines numbered 1 – 6. The box and lines were black on a white background. The box randomly appeared vertically centered and horizontally justified on the left or right side of the screen and flashed on and off at 100-ms intervals until a response or the end of the

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response interval. Participants pressed a key corresponding to the same or opposite side of the screen as the flashing box, depending on the experimental condition. The *1* and *3* keys were additionally labeled *L* and *R* and represented the left and right sides of the screen, respectively. Right-handed participants responded with the *1* and *3* keys on the numerical keypad, and left-handed participants used the *1* and *3* keys from the number row in the alphanumeric keypad. Participants were instructed to make this decision rapidly, and feedback on valid trials consisted of the response time, a running tabulation of the mean response time per trial block, and encouragement to beat that mean response time on subsequent trials. Trials in which the wrong response was made were immediately void and, when the speeded task was used with running span, the memoranda were not collected and a new trial of the same length was added at random among the remaining trials.

Procedure

Participants were tested individually in a single session lasting 55 minutes or less. Participants completed three task segments: (1) the speeded task practice, which was always first, comprising pro- and anti-press task trial blocks counterbalanced for order; (2) a memory span task alone; and (3) memory span combined with the speeded task. The order of Task Segments 2 and 3 was counterbalanced across participants, and the order of pro- and anti-press trial blocks within each of these was counterbalanced across participants but was the same as in Task Segment 1.

Participants in a dual task condition completed Task Segments 1 – 3 twice, once with concurrent articulatory suppression and once with concurrent knee tapping. These participants were counterbalanced for whether they first received trial blocks with concurrent articulatory suppression or tapping tasks. Within those trial blocks, though, the task order for Task Segments 1 – 3 was unchanged.

The speeded task practice (Task Segment 1) consisted of 2 practice and 18 test trials each for the anti- and pro-press procedures. The memory-span-only task (Task Segment 2) consisted of 2 practice and 18 test trials. The procedure for memory span combined with the speeded task is illustrated in Figure 1. This task included 2 practice and 18 test trials in each trial block, with anti- and pro-press speeded task conditions performed in two separate blocks counterbalanced for order.

In the memory-span-only task, participants were permitted unlimited response time for the memory response but were encouraged to perform it accurately and quickly. Participants initiated each trial by key press, after which a 250-ms visual fixation cross appeared, followed by the flashing box. Recall was permitted immediately after the offset of the digits, and the response box was vertically and horizontally centered. In the memory span task plus speeded task condition, participants had to make the speeded task response under time pressure; they were permitted a period of time equivalent to their mean response time in the speeded task practice plus one standard deviation, and longer reaction times invalidated the trial. Following the speeded task response, participants typed the memory-span digits in serial order. Responses

[1]We believe that time pressure was critical in preventing covert verbal rehearsal. In the absence of time pressure in our speeded task decision, participants could delay their response in order to rehearse or otherwise prepare their response on the running span task. For instance, it is possible that they might delay the responses until the list-final digit sequence could be memorized, for subsequent recall from what Ericsson and Kintsch (1995) have termed "long-term working memory" (see also Cowan, 1995; Nelson & Goodman, 2003). As evidence of this, consider an experiment in which we replicated most of the Experiment 1 procedure but with unlimited time for what we have otherwise called the "speeded task" response. The anti-press response did not affect running span performance in the absence of time pressure. Response speeds were more than a half second slower than in Experiment 1. Running-span scores, which were for trials with a correct speeded task response only, did not significantly differ with the anti-press (M = 2.37, 95% CI = ± .17) or pro-press (M = 2.49, 95% CI = ± .17) responses (ΔM = 0.12, SE = 0.10), $t(27)$ = 1.06, *ns*. Anti- (M = 975 s, SD = 506) and pro-press (M = 1001 s, SD = 492) response times did not significantly differ (ΔM = 26 ms, SE = 58.2), $t(27) < 1.0$, *ns*. The results must be interpreted with some caution, because the experiment did not include a no-press control condition.

were shown on the screen in the box that had appeared for the speeded task, a 3” × 6” rectangular response box containing six numbered lines, one for each digit from the end of the list.

Design

The design of the seven experiments and the number of participants per experiment are summarized in Table 1. The experiments have the same basic procedure, only differing with respect to the type of memory task (running or fixed), the presentation rate of the memoranda (fast or slow), and the absence or presence (and kind) of dual task (co-articulation, tapping, or none). Each memory task was followed by the speeded interpolated task with anti-press, propress, and control conditions.

EXPERIMENT 1A: FAST RUNNING SPAN (NO DUAL TASK)

Results

We first describe the primary Experiment 1a data, namely the effects of the speeded task on running memory span. Next we describe the details of the speeded task itself.

Running Span—Running span was defined simply as the mean number of digits recalled in the correct serial position. Figure 2 (E1a) depicts a main effect of running span and shows that mean running-span scores were lower in the anti-press condition than in the pro-press or control conditions, which did not differ. Statistical analyses supporting this conclusion were based on the proportion correct across serial positions. Specifically, an ANOVA for repeated-measures tested whether running span scores, for trials with a correct speeded task response only, varied as a function of the speeded task conditions (anti-press, pro-press, and control), the serial positions to be recalled (the last six positions, which we label 1–6 for convenience), or the interaction of these variables. The critical effect for our hypotheses, a main effect for the speeded task, was significant. The ANOVA and pairwise comparisons are reported in Table 4.

A significant main effect of serial position, $F(5, 115) = 101$, $MSE = .03$, $p < .01$, indicated a strong recency advantage, as one can see in Figure 3. The interaction of speeded task×serial position was not significant, $F(10, 230) = 1.17$, $MSE = .01$, *ns*. We entertained the hypothesis that the differences between conditions in running-span scores could be attributed to a small, though significant, difference in response times to the anti- and pro-press decisions (described below). Lower scores for the anti-press condition hypothetically could result from a slightly longer period for decay of the passive buffer information in that condition. To equate reaction times for these speeded-task conditions, the 42 trials with the longest response times among all trials for all participants in the anti-press condition were dropped. Even with the mean response times for the anti- and pro-press conditions equated (at 364 ms), the pattern of results for running span remained unchanged. The ANOVA main effect of the speeded task was still significant, $F(2, 46) = 7.95$, $MSE = .196$, $p < .01$, and subsequent orthogonal pairwise comparisons still showed that the anti-press ($M = 2.07$, $SD = .70$) but not the pro-press condition ($M = 2.45$, $SD = .68$) differed significantly from the control ($M= 2.56$, $SD = .75$).

Speeded task

Practice phase: It was predetermined that, in the speeded-task practice phase, trials with reaction times less than 200 ms (none actually occurred) or greater than 1000 ms (reported in Table 2) would be deemed spurious and dropped from the analysis, and the computer re-ran those trials. Performance on the speeded task practice was used to establish each participant’s baseline performance. Means with standard deviations for errors and reaction times to the antiand pro-press decisions are reported in Table 2. Significant differences, as determined by paired-samples t-tests, are also indicated in Table 2. Statistical analyses of these data were unremarkable here and in the remaining experiments, so further discussion is omitted to conserve space.

Speeded task combined with running span: Table 3 shows means with standard deviations for errors and reaction times to the anti- and pro-press decisions of the speeded task when carried out along with running span. Trials with reaction times under 200 ms (1 in the anti-press and 6 in the pro-press condition) were excluded from the analysis, as were trials with reaction times above the speeded-task practice mean plus 1 SD (time-out trials shown in Table 3).

In 10 of the 12 experimental conditions reported in Table 3, many more time-out trials occurred in the pro-press condition than in the anti-press condition, despite the mean reaction times in practice being similar. This could be due to the increase in SD from single to dual-task condition (i.e., combining the speeded task with running span) that occurred in the pro-press task but not the anti-press task. There was also a second critical factor. Specifically, comparing Table 2 and Table 3, one can see that, by the end of practice, performance appears to have reached an asymptotic speed for pro-press trials (which were 1 ms slower when combined with a memory test than they were in the practice phase) whereas more improvement occurred during the memory test phase for the anti-press trials (which were 15 ms faster when combined with a memory test than they were in the practice phase).

More errors were made in the anti-press than pro-press speeded-task condition. Trials in which there was an error in the decision were dropped and did not influence the computation of mean reaction times or running-span scores. Accurate pro-press decisions were also made in significantly less time than anti-press decisions. Paired-subjects t-tests supporting these conclusions are reported in Table 3, along with accuracy and reaction time data for the speeded task responses in the remaining experiments. Subsequent discussion of this data would be redundant, so further discussion is omitted to conserve space.

Replication Experiment—We replicated the anti-press disadvantage in another experiment (N = 23), in which the running span task as described above served as the control condition. The manipulation new to that experiment (proactive interference from previous items; for details see the appendix) did not prove effective, but the control condition is nonetheless important as it replicates the anti-press disadvantage with new participants in a different experimental context. A repeated-measures ANOVA identified a speeded task effect in an analysis of the anti-press, pro-press, and control conditions, $F(2, 44) = 4.18$, $MSE = .26$, $p < .02$. Orthogonal pairwise comparisons confirmed that span scores were significantly lower in the anti-press condition ($M = 2.12$, $SD = .71$) than in either the pro-press ($M = 2.48$, $SD = .83$) or control ($M = 2.50$, $SD = .75$) conditions, which themselves did not differ.

Discussion

We favor the view that attention is used in running span with a fast presentation in a way that it is not used in many other forms of recall. Specifically, given that it is impossible to update a capacity-limited, attention-demanding store as the list presentation proceeds, after the list ends it is necessary for attention to be focused on an unanalyzed sensory and/or phonological record to allow the extraction of items into the limited store at that time. The results of Experiment 1a are consistent with that hypothesis, along with the corollary that a speeded, interpolated task can compromise working memory when it, too, depends on the same attentional resource (Cowan, 2001; Cowan et al., 2005). Specifically, the fact that the anti-press condition interfered with running span suggests that there is a shared attentional resource.

The fact that the effect of the nature of the speeded task was relatively small (0.4 – 0.5 item) suggests that storage may rely only partly on the shared resource. Cowan (1988, 1995, 2001) allowed for activated memory outside of the focus of attention, serving a function comparable to passive memory buffers. In the present experiment, it could take the form of both auditory sensory- and phonological memory representations of the spoken digits. The reason that the effect of distraction was not even larger than it was could be that the memory retrieval process could return to a passive store after the completion of the interpolated, speeded-decision task, albeit to a store that, by then, was somewhat degraded. We would thus anticipate more forgetting were the retention interval longer, though we did not test this prediction.

However, we did test several other hypotheses regarding the effect of the conditions during encoding on final recall. To anticipate the outcome, these factors – *speed* of the digit presentation, and the presence or absence (and difficulty when present) of *distraction* during encoding – had systematic effects when acting in unison.

EXPERIMENT 1B: SLOW RUNNING SPAN (NO DUAL TASK)

We provided time for rehearsal during the running span task, thereby reducing the need to use attention in the apperception of the running-span items (Hockey, 1973). As indicated in Table 1, the task requirements remained unchanged from Experiment 1a but for the decrease in the presentation rate. (Experiment 1b was the control condition in a larger experiment, the details of which are described in the appendix.) Mean running span scores are depicted in Figure 2 (E1b). A repeated-measures ANOVA failed to detect a difference among the anti-press, pro-press, and control (no speeded task) conditions, $F(2, 40) = 1.41$, $MSE = .83$, *ns*. Thus, the speeded task failed to have a statistically significant effect on memory for the running span digits when we slowed the presentation rate to permit active updating and rehearsal during encoding.

EXPERIMENT 1C: SLOW RUNNING SPAN WITH CONCURRENT TASKS

A tacit assumption of the experiments thus far has been that a rapid presentation rate has much the same effect as articulatory suppression on encoding. In this experiment articulatory suppression was added during encoding on the slow-paced running span task to prevent rehearsal. A non-verbal dual task, knee tapping with the non-dominant hand during presentation of the memoranda, was implemented separately and served as a comparison.

Mean running span scores for the tasks with co-articulation and tapping are depicted in Figure 2 (E1c). The interpolated speeded task significantly affected memory for the running span digits in both the task with articulatory suppression and the task with tapping. ANOVAs and pairwise comparisons for these simple effects are given in Table 4. [The experiment-specific interaction between speeded task condition (anti-press, pro-press and control) and dual-task distraction during encoding (articulatory suppression & tapping) was evaluated by means of a repeated-measures ANOVA but was not significant, $F(2, 40) = 1.40$, $MSE = .21$, *ns*.]

Articulatory suppression made encoding the running span digits difficult, in spite of the fact that the presentation rate was slowed to permit rehearsal. This is evidenced in the negative effect of the speeded task (anti and pro) on running memory span. Tapping had less impact on encoding, as indicated by the significant difference between scores in the pro- and anti-press conditions of the task with tapping.

EXPERIMENT 1D: FAST RUNNING SPAN WITH CONCURRENT TASKS

This final running span experiment demonstrates the combined effects of unpredictability, speeded presentation rate, and dual-task distraction during encoding on final recall. The prediction was that any distraction, even the pro-press speeded task, during the retention interval would hurt performance relative to the no-press control. At the rapid rate of presentation, articulatory suppression would not only make rehearsal all the more impossible, but it would make scheduling the speeded task responses difficult as well. We speculated that tapping would likewise affect scheduling.

Mean running span scores for the tasks with co-articulation and tapping are depicted in Figure 2 (E1d). The effect of the speeded task on memory for the rapid running span digits was significant in the both the task with articulatory suppression and the task with tapping. ANOVAs and pairwise comparisons for these simple effects are given in Table 4. [The experiment-specific interaction between speeded task condition (anti-press, pro-press and control) and dual-task distraction during encoding (articulatory suppression & tapping) was evaluated by means of a repeated-measures ANOVA but was not significant, $F(2, 34) < 1.0$, *MSE* = .17, *ns*.]

It was the case for both the task with co-articulation and the task with tapping that running memory scores were better in the control condition than either the anti-press or pro-press conditions, which themselves did not differ. Given the unpredictability of the running span lists and the difficulty of combining rapid presentations with articulatory suppression or tapping, it was the case that the minimal amount of attention required even for the pro-press condition was enough to disrupt memory retrieval.

EXPERIMENT 2A: SLOW FIXED-LENGTH LISTS WITH CONCURRENT TASKS

Our view is that rehearsal is difficult, if not impossible, in running span at the rapid presentation rate in Experiment 1a. We attribute this not only to the speeded presentation rate but also the unpredictability of the running span list (cf. Bunting et al., 2006; Hockey, 1973). In our view, the absence of rehearsal leads to a reliance on attention at the time of retrieval and therefore to susceptibility to the anti-press version of the speeded task. A similar susceptibility theoretically could be achieved in a fixed-list, slower-presentation memory task if articulatory suppression were required. Therefore, our objectives in this next series of experiments were to determine (1) whether the speeded task would interfere with memory for fixed-length lists when articulatory suppression was added and (2) whether predictability is requisite for this effect.

Results

As indicated in Table 1, participants completed a 6-digit memory span task, once with articulatory suppression and once with knee-tapping. Mean list memory scores for the task with co-articulation and the task with tapping are depicted in Figure 2 (E2a). An ANOVA for repeated-measures was used to test whether memory (i.e., proportion correct on the span task) varied as a function of the speeded task conditions (anti-press, pro-press, and control), the concurrent-task conditions (articulatory suppression and tapping), serial position, or some interaction of these variables. The speeded task by concurrent task interaction, which is critical to our primary hypothesis, was significant, $F(2, 34) = 4.00$, *MSE* = .04, $p < .03$. The locus of this interaction was that the anti-press speeded task had a diminishing effect on list memory scores in the task with articulatory suppression but not the task with tapping. There was thus a simple effect of the speeded task condition for list memory with articulatory suppression, but not with tapping (see Table 4 for the ANOVAs and pairwise comparisons).

The overall analysis also produced main effects of speeded task, concurrent task, and serial position, $F(2, 34) = 5.64$, *MSE* = .10, $p < .01$, $F(1, 17) = 216$, *MSE* = .03, $p < .01$, and $F(5, 85) = 61.62$, *MSE* = .02, $p < .01$, respectively. Figure 2 (E2a) shows that performance was highest overall for the control condition and lowest overall for the anti-press condition, and that performance was higher with tapping than with articulatory suppression. Figure 3 further shows that the effect of serial positions was curvilinear; thus resembling many previous studies of serial recall (e.g., Page & Norris, 1998). There was a concurrent task by serial position interaction, $F(5, 85) = 17.84$, $MSE = .01$, $p < .01$, which appears to indicate a detrimental effect of suppression compared to tapping, especially in the medial serial positions because bowing in the function was accentuated with suppression. Mean list memory scores (with standard errors) at serial positions 1 – 6 were .85 (.02), .70 (.02), .61 (.02), .49 (.02), .50 (.02), and .79 (.03), respectively, for the task with articulatory suppression, and .95 (.01), .90 (.02), .84 (.03), .77 (.04), .78 (.03), and .93 (.02), respectively, for the task with tapping. Paired-comparison *t*-tests indicated that scores were significantly lower for the task with articulatory suppression at every serial position (alpha was adjusted to .008 for multiple comparisons). There was neither a speeded task by serial position interaction nor a speeded task by concurrent task by serial position interaction, $F(10, 170) < 1.0$, $MSE = .01$, *ns*, and $F(10, 170) < 1.0$, $MSE = .01$, *ns*, respectively.

Response times to the anti- and pro-press decisions were not significantly different but still not perfectly equal so, as in Experiment 1a, we entertained the hypothesis that this could be why list memory scores differed in the task with articulatory suppression. To equate reaction times for the speeded-task conditions in list memory with articulatory suppression, the 20 trials with the longest response times among all trials in the articulatory suppression condition for all participants in the anti-press condition were dropped. Even with the mean response times for the anti- and pro-press conditions equated (at 389 ms), the pattern of results for list memory remained unchanged. Critical to our hypothesis, the ANOVA main effect of the speeded task was still significant, $F(2, 34) = 6.03$, $MSE = .66$, $p < .01$, and subsequent orthogonal pairwise comparisons still showed that the anti-press ($M = 3.45$, $SD = .76$) but not the pro-press condition ($M = 3.95$, $SD = .67$) differed significantly from the control ($M = 4.39$, $SD = .77$).

Discussion

This experiment successfully replicated the speeded task effect (i.e., lower memory span with the anti-press than the pro-press) but with a fixed-list memory task with articulatory suppression. Our position here, as in the Experiment 1 series of experiments, is that attention is sometimes needed to convert information from passive storage and/or precategorical sensory memory to a form in which it can be recalled, as when rehearsal is prevented during encoding. The anti-press condition introduced competition for attention precisely at the time that it was needed for digit recall and hence detracted from list memory scores.

The tapping task was innocuous in so far as it did not prevent rehearsal of the digits and, therefore, did not interfere much with the function of attention to retrieve, store, and recall the digits. Under these circumstances, we think that memory is maintained via a passive storage mechanism, such as phonological memory in Baddeley's (2000) model or the activated portion of long-term memory (which includes both sensory and categorical features) in Cowan's (1995) model. In this case and unlike the situation in which rehearsal was prevented, the contents of passive storage has already been attended and interpreted at the time of encoding, so it is already in a retrievable form and takes less attention at the time of retrieval.

Comparison of serial position effects across two very different experiments yielding attention-related effects—The serial position patterns displayed in Figure 3 are telling of the similarities and differences between recall in fixed-list memory with articulatory suppression (the current experiment) and running span at the rapid presentation rate (Experiment 1a). The recency pattern (i.e., performance at serial positions 4 – 6) is essentially identical in both tasks. The presence of the primacy effect for the fixed-list memory tasks clarifies why the number correct summed across serial positions is higher for fixed lists than for running span (Figure 2 E2a versus E1a). It is not yet clear from the literature just why the primacy effect occurs. It could be accounted for on the basis of item distinctiveness (Neath,

1999) or it could be tantamount to a primacy gradient (Farrell & Lewandowsky, 2004;Page & Norris, 1998). In the former case, the primacy advantage is attributed to the fact that primacy items are distinct in memory because there are no immediately preceding items with which they can become confused. In the latter case, there is superior encoding strength for the first item by virtue of its order and degraded strength for subsequent items in proportion to their displacement from the starting point. Page and Norris further clarify that the primacy gradient could be an effect in which the activation of each new item is diminished because activation must be shared with already-existing items, or it could be based on how far each item is from a context-marker at the beginning edge of the list. The latter account may be inconsistent with the finding that it is the relative location of an item in a list that is most important for recall, not its absolute distance from the beginning of the list (Henson, 1999). In any case, items for recall in running span are not similarly distinct as they do not come at the beginning of the list (see also Hockey & Hamilton, 1977).

The serial position patterns are inconsistent with a decay account of forgetting. There was superior recall for the fixed list items in spite of the fact that rehearsal was prevented via articulatory suppression and the presentation rate was slower than in running span. As opposed to our preferred accounts of the primacy effect for fixed-list recall, decay would thus necessarily predict superior performance for running span rather than the fixed-list task. Of course, it is possible that there is decay obscured by other, more potent factors in recall.

In Experiments 1a and 2a, we obtained effects of the difficulty of a task intervening between stimuli and responses in two very different situations (running span, and fixed span with articulatory suppression). The remaining Experiments 2b and 2c allow us to reveal a more extensive pattern by including various permutations of the task conditions, including *predictability* of the digit list, *speed* of the digit presentation, and the presence or absence (and difficulty when present) of *distraction* during encoding.

EXPERIMENT 2B: FAST FIXED-LIST MEMORY WITH CONCURRENT TASKS

As indicated in Table 1, the task requirements remained unchanged from Experiment 2a but for the decrease in the presentation rate. Mean digit recall on the anti-, pro-, and no (control) speeded task conditions for the tasks with co-articulation and tapping are depicted in Figure 2 (2b). The effect of the speeded task on memory for the rapidly presented, fixed-length lists was significant in both the task with articulatory suppression and the task with tapping. ANOVAs and pairwise comparisons for these simple effects are given in Table 4. [The experiment-specific interaction between speeded task condition (anti-press, pro-press and control) and dual-task distraction during encoding (articulatory suppression and tapping) was evaluated by means of a repeated-measures ANOVA but was not significant, $F(2, 34) = 1.46$, $MSE = .17$, *ns*.]

For the task with articulatory suppression, scores in the control condition significantly exceeded scores in the anti-press and pro-press conditions, which themselves did not differ (see Table 4). The pattern was identical for the task with tapping. This effect is similar to the effect for running span at the rapid presentation rate and with articulatory suppression (Experiment 1d). As we argued there, articulatory suppression may add to the demands on attention at the moment of the speeded task response. This competition might limit the extent to which the focus of attention can zoom out to apperceive the unrehearsed items in sensory or phonological memory at the required time.

Predictability continued to be highly important to memory for the digits. Even with articulatory suppression during encoding and the rapid presentation rate, memory for the digits was still better than in Experiment 1d with the unpredictable running span task. However, predictability alone did not diminish the need for attention during the retention interval, as indicated by the negative effect of the anti-press speeded task on memory for digits, either for the task with tapping or articulatory suppression.

EXPERIMENT 2C: FAST AND SLOW FIXED-LENGTH LISTS (NO DUAL TASK)

The concurrent-task conditions (articulatory suppression & tapping) were eliminated from the fixed-length list memory task. Presumably, subjects could thus adopt an active rehearsal strategy, at least when the digits were presented at a sufficiently slow pace, hence mitigating the need for attention during the retention interval. Participants completed the tasks listed in Table 1 (2c).

Mean list memory scores for the fast and slow presentation rates are depicted in Figure 2 (2c). The scores varied as a function of the difficulty of the speeded task in the rapid presentation rate condition but not in the slow presentation rate condition. ANOVAs and pairwise comparisons for the simple effects of presentation rate are given in Table 4. [The experiment-specific interaction between speeded task condition (anti-press, pro-press and control) and digit presentation rate (rapid and slow) was evaluated by means of a repeated-measures ANOVA but was not significant, $F(2, 38) < 1.0$, $MSE = .14$, *ns*.]

The results of this experiment are consistent with our previous observations of the running span task at rapid and slow rates of presentation (Experiments 1a and 1b). Namely, the opportunity for rehearsal during encoding in the slow presentation rate condition – either in Experiment 1b with the slow-paced running span or here with the slow-paced, fixed-length list task – reduced the need for attention during the retention interval. Although the fixed-length lists were predictable and short by comparison to the running span lists, the anti-press speeded task had a small though significant detrimental effect on memory for the lists at the rapid pace, which we attribute to competing demands for attention during the retention interval.

Cross-Experiment Comparisons

The effect of the speeded interpolated task on memory for digits was tested a total of 12 times, under different conditions, in the seven previous experiments. The digit-memory tasks varied along three important dimensions: (1) the ease of anticipating the number of digits in the list, (2) the digit presentation rate, and (3) the absence or presence of distraction during encoding (and the difficulty of the distraction task when present). The speeded interpolated task provided interference during the retention interval of the digits and varied in the degree of difficulty or attentional demand (anti-press was the more difficult condition).

Figure 2 shows all 12 of these conditions. For each span task, an asterisk (*) indicates that the condition shown (anti-press or pro-press) differed significantly from the no-press control condition. A number of main effects pertinent to our primary variables (predictability, presentation rate, and dual-task distraction) are apparent. Predictability – whether the digit list was fixed at 6 items or long and unpredictable – had a significant effect on performance; scores across all conditions were almost twice as high with the fixed list task as with the running span task.

The effect from the speed of the presentation rate was more subtle and was most apparent in the tasks without a dual-task component. A visual comparison of the control conditions without a dual task shows that subjects benefited from the ability to rehearse and update during presentation of the running span digits but not the fixed-length list digits. The addition of the anti-press interpolated task, however, hurt performance, thus indicating that rehearsal during the encoding interval may not matter as long as the list is relatively short and predictable and attention is available immediately following presentation of the digits.

The articulatory suppression condition clearly hurt performance across the conditions relative to the conditions without a secondary task during encoding. Tapping, while meant to be a fairly innocuous, repetitious motor activity, appeared to have a small though negative effect on performance in all but the slow-paced, fixed-length list task. The effect was not as substantial as that with articulatory suppression. We attribute this to difficulty coordinating competing motor responses for the knee tapping and interpolated key-press components of the task.

In addition to these main effects, there is systematic evidence of the three factors (dual task potency, speed of presentation, and predictability of list length) all working together. In Figure 2, we have labeled groups of conditions with extreme results Group A (no effect of either pro- or anti-press tasks) and Group B (effects of both), Thus, in Group B, fast presentation with either articulatory suppression or unpredictability (running span) produced significant effects of both anti- and pro-press compared to the control. Conversely, in Group A, slow presentation with either no dual task or with a mild dual task and predictable presentation (fixed span) produced neither effect. The remaining, intermediate conditions produced an effect of anti-press but not pro-press. We attribute this pattern to the stability of encoding. When encoding was highly stable, as in Group A, distraction during retrieval made little or no difference. When encoding was not stable, as in Group B and to a lesser extent in the remaining tasks, distraction during retrieval made a difference. We hasten to add that not every variable had a consistently strong effect by itself, but Figure 2 shows that the pattern of influences of the variables in combination was clear and in accord with expectations.

GENERAL DISCUSSION

Experiment 1a (and its replication described in that results section) and Experiment 2a demonstrated that the attentionally-demanding, anti-press decision task impaired working memory when the prepotent tendency to orient to the flashing box did not the match the task goal. It is easy to see why encoding and subvocal rehearsal are difficult in a running span procedure with a rapid presentation rate (Experiment 1) or in a fixed-length procedure with a slower presentation rate along with articulatory suppression (Experiment 2). We assume that under these circumstances, attention is needed in the time following the presentation and just preceding the response to extract information from the passive sources of memory (e.g., sensory memory and/or activated long-term memory) to more meaningful units that can be used in the response. The difficult, speeded anti-press (opposite-side) task draws attention from retrieval at the critical moment and therefore limits memory for the digits. When attention has to "zoom in" to avoid the incorrect, prepotent response in the opposite-side task, it is less available to "zoom out" to apprehend as many digits as possible in the phonological stream at the same time.

The disadvantage of the anti-press condition relative to the pro-press condition was also observed in Experiment 1c, the slow-paced running span task with tapping. This time, encoding and rehearsal were possible, but there was more than one attentional demand at recall. At the offset of the digits, which was unpredictable, subjects had to coordinate the speeded task response while coordinating the tapping response. The confluence of these factors was detrimental to recall, but more so in the anti-press condition than in the pro-press condition.

One might think that a role of attention in short-term memory retrieval can be taken for granted, but we found that the conditions needed to observe a fleeting use of attention for retrieval are delicate. In Experiment 2a, there was no effect of pro- or anti-press tasks for the recall of fixed-length lists presented during tapping (as opposed to articulatory suppression). This suggests that the amount of attention that is needed for retrieval is greater when articulation is blocked than when it is not blocked. No effect of attention was observed in two other instances in which rehearsal presumably was possible (see Figure 2 and Experiments 1b and 2c). When rehearsal is possible, as in these conditions, it can be used to maintain the memoranda in a passive store, such as phonological memory in Baddeley's (2000) model or the activated portion long-term memory (which includes both sensory and categorical features) in Cowan's (1995) model. Thus, the effect of attention we have observed was not general across these tasks.

It turned out that negative effects of anti-press and articulatory suppression were not always absolute, nor were the effects of pro-press and tapping always benign. Rather, the most reasonable conclusion to reach based on our data seems to be that the various influences on performance come in degrees. The pro-press responses and tapping had some detrimental effect on performance, but not as much as anti-press and articulatory suppression. We found that participants could engage in even the anti-press speeded task with little or no detectable cost when there was unlimited time in which to make the speeded task response (see the discussion following Experiment 1a) or when rehearsal was not blocked; for instance, as when the running span or list memory items were played slowly and in the absence of any concurrent-task distraction (see Experiment 1b and Experiments 2c). Conversely, even the pro-press may be attention demanding if multiple tasks have to be scheduled under time pressure (e.g., attending to rapidly-presented digits in an articulatory suppression condition; Experiments 1d and 2b). These results are consistent with other research showing that when given the opportunity, participants have remarkable flexibility in how they allocate their attention among multiple complex tasks (Barrouillet et al., 2004; Friedman & Miyake, 2004a; Gillie & Broadbent, 1989).

The ability to recover following response conflict has been ascribed to executive control processes (Stürmer, Seiss, & Leuthold, 2005). The likelihood of making an error when there is a response conflict probably depends on the extent to which one has been primed to expect a response match. We would anticipate a larger effect from the response mismatch had we mixed anti-press and pro-press trials rather than testing them in discrete blocks, especially if a predominant number of the trials were pro-press (cf. the disproportionate number of congruent trials in Kane & Engle's, 2003, research on the Stroop effect).

The results are consistent with prior research demonstrating a relationship between attentional control and goal maintenance (see Engle, 2002). Several recent studies have shown that performance on traditional complex working memory span tasks is positively related to some largely attentional phenomena, including lapses in focused attention in a dichotic listening paradigm, visual orienting errors in the antisaccade paradigm, and the Stroop effect (for examples of each of these see Conway, Cowan, & Bunting, 2001; Kane et al., 2001; Kane & Engle, 2003, respectively). On the surface, at least, tasks such as these have little similarity to span tasks or other memory tasks in general, but such findings suggest that attentional control is important to the criterion validity of working memory. One explanation of this finding is that goal maintenance and working-memory storage rely to some extent on the same resource, which may be allocation of the focus of attention (Cowan, 1999, 2001). The working-memory theory of Baddeley (2000) also might accommodate the present results, by sticking to the assumption that the episodic buffer depends on attention (similar to long-term episodic memory; see Cowan, 1995) and is therefore more susceptible to distraction than are the phonological and visuospatial buffers.

One other study supports the point we are making, in the converse manner, by showing an effect of storage on processing. Eenshuistra, Ridderinkhof, and van der Molen (2004) used pro-and antisaccade tasks and showed that the elderly were impaired in antisaccade task performance only when they had a concurrent storage load during the processing task. The memory load apparently made it difficult for them to concentrate on the goal maintenance task, confirming the proposal (Cowan et al., 2005) that both goal maintenance and working-memory storage rely on a common resource such as attention.

Future work should address the criterion validity of running span and ordinary span with articulatory suppression. Cowan et al. (2005) recently showed that running span, at least at the rapid presentation rate, is an accurate and reliable measure of working memory and has good criterion validity. There is an ample literature suggesting that suppressing rehearsal may be critical for the potency of working-memory tasks as predictors of cognitive aptitude, and that the use of attention for storage and recall might be the critical factor defining the best working-memory tests.

We have argued that the running span task and the fixed-length list task with articulatory suppression measure the scope (i.e., capacity) of attention. That is, attention must be used to capture as many digits as possible from a sensory or phonological memory trace at the end of the list, before that representation fades. It follows, therefore, that individual differences in the scope of attention underlie the criterion validity of such span tasks (Cowan et al., 2005). The current experiments in all but the most stable encoding conditions showed that the difficult speeded task limited the mnemonic function of attention, and thus the span tasks no longer reflected the scope of attention.

Conclusion

Overall support for the use of attention at retrieval must be made cautiously at this point. In sum, a brief visual distraction during the retention interval in a running span task (Experiment 1a) or a fixed-list-length memory task with articulatory suppression (Experiment 2a), namely choosing the opposite side of the screen relative to a flashing box, was enough to interfere with recall. Other factors mitigated this effect, as when there was the opportunity for rehearsal during encoding (the slow presentation with no dual task in Experiments 1b and 2c or with tapping in Experiment 2a). Overall, the interpolated task effect suggests that attentional control, as necessary for goal maintenance, and temporary storage may share an attentional resource. Consistent with Cowan (2001), attention might zoom in to maintain a goal or zoom out to apprehend multiple items. Attention can be used for goal maintenance in the face of distraction, as in the anti-press response in the speeded task, but only at a cost to the use of attention for the apprehension of items to be recalled.

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Appendix

Methodological Details of the Experiment 1a Replication and Experiment 1b

We hypothesized that memory for irrelevant, early list items (proactive interference) may contribute to the difficulty recalling the last six items in running span. To test this hypothesis, we tested participants in two sets of running span tasks. Both sets included the speeded task practice, running span with the speeded task, and a running span only control. In the first set of tasks, the digits were completely random (the procedure was identical to that described in Experiment 1a). In the second set of tasks, we manipulated the novelty of the digits. In one block of running span trials, the first 3 of 6 to-be-recalled digits were novel to that trial. In a second block of trials, the last 3 of 6 to-be-recalled digits were novel to that trial. We conducted this experiment with the digits at a rapid presentation rate (4 digits/s), which is the task reported in the replication of Experiment 1a. We also conducted this experiment with the digits at a slow presentation rate (1 digit/s), which is the task reported in Experiment 1b. While we found an effect of novelty in both experiments, the results of that manipulation are not easily interpretable and will require further experimentation.

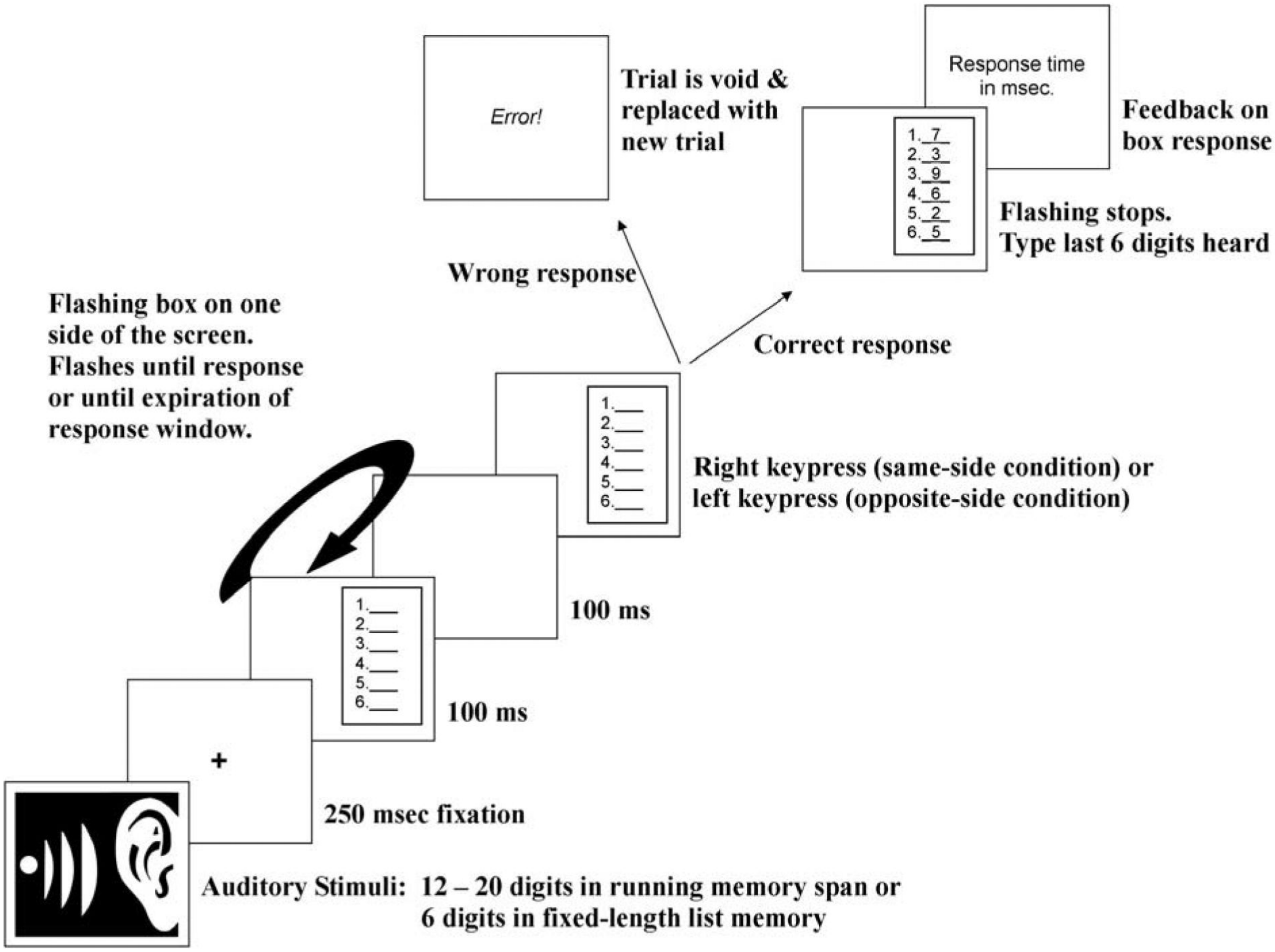

Figure 1.
General experimental design. The speeded interpolated task followed presentation of an auditory running memory span trial (12 – 20 random digits) or an ordinary memory span trial (6 random digits). The box flashed on either the right or left side at random. Feedback to accurate responses in the speeded task included reaction time on the current trial, mean reaction time for all trials so far in the block, and encouragement to beat the current response time on the next trial. Incorrect responses on the speeded task voided the trial, and a replacement trial with the same number of digit stimuli was added at random among the remaining trials.

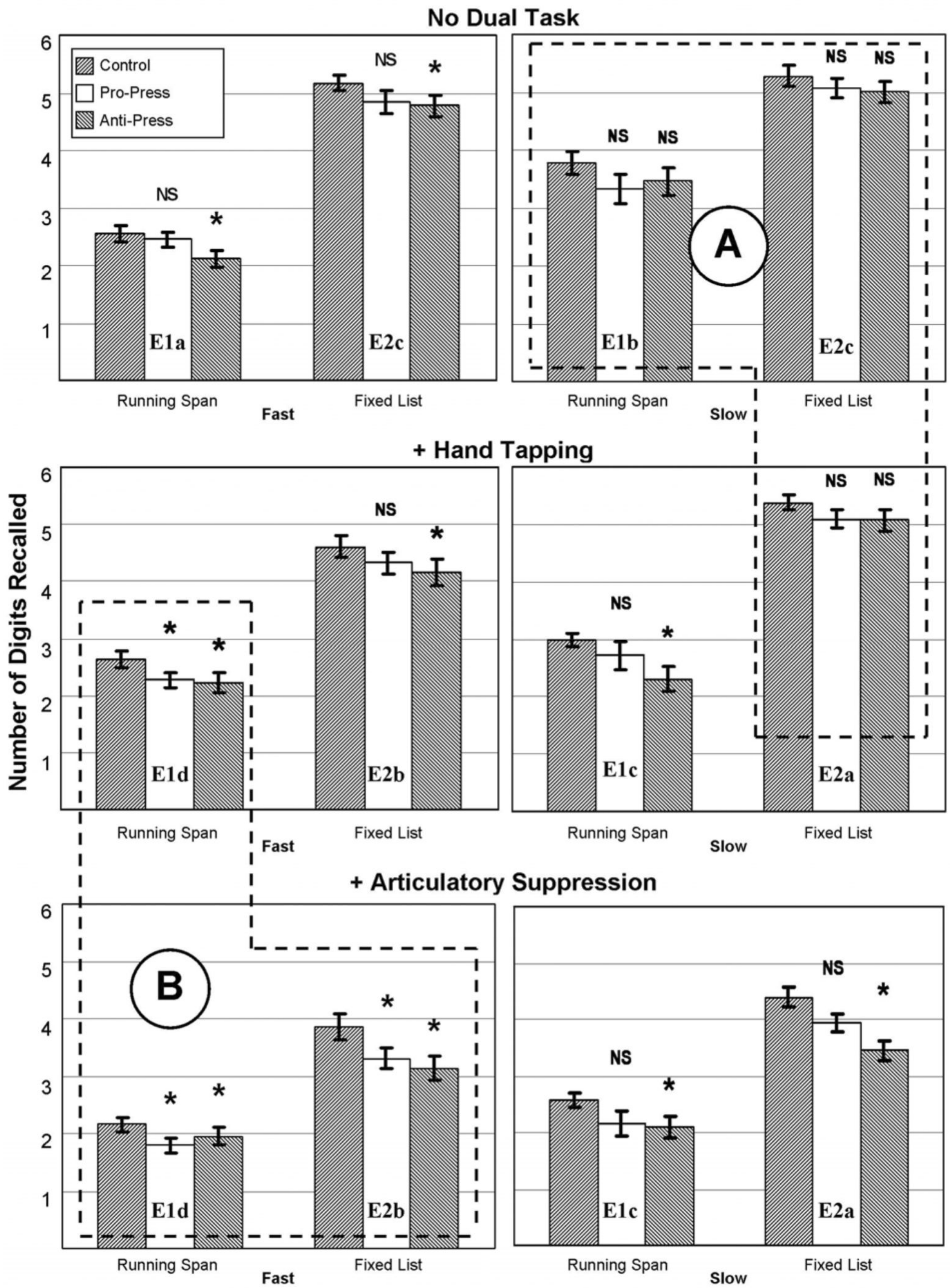

Figure 2.

The effect of the speeded interpolated task on memory for digits in all 12 task conditions across the 7 experiments. The digit lists were either fixed or unpredictable, the digit presentation rate was fast (4/s) or slow (1/s), and the secondary task, when present, was easy (hand tapping on knee) or difficult (articulatory suppression). Note: * indicates a significant difference from the interpolated task control for that task, and NS indicates that the effect was not significant. E1a-E2c indicate the numbered experiment that was the source of the data (e.g., E1a = Experiment 1a). Error bars are 95% within-subject confidence intervals (Loftus & Masson, 1994).

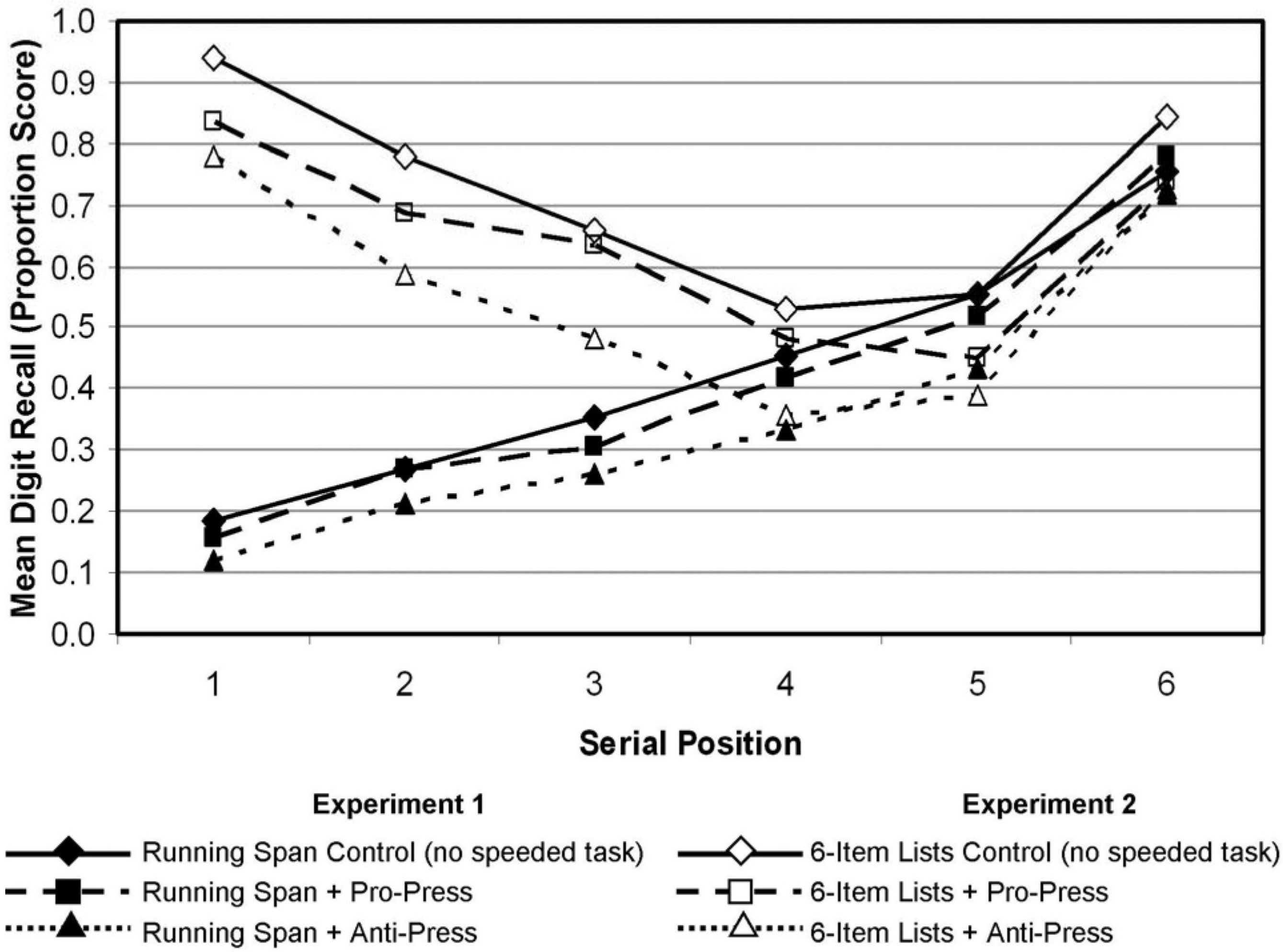

Figure 3.
Proportions correct for running span (Experiment 1a) and fixed-length lists with articulatory suppression (Experiment 2a) at each of six serial positions as a function of the anti-press, pro-press, or no (control) speeded decision task interpolated between the span stimuli and responses. Data are for trials with correct speeded-task responses only.

Table 1

The Experimental Design

Experiment & Condition No.	Memory Span Task(s)	Digit Presentation Rate	Dual Task	*N* (No. of females)
1a	Running	Fast	None	24 (10)
1b	Running	Slow	None	21 (16)
1c – 1	Running	Slow	Co-articulation	21 (11)
1c – 2	Running	Slow	Tapping	21 (11)
1d – 1	Running	Fast	Co-articulation	18 (16)
1d – 2	Running	Fast	Tapping	18 (16)
2a – 1	Fixed	Slow	Co-articulation	18 (6)
2a – 2	Fixed	Slow	Tapping	18 (6)
2b – 1	Fixed	Fast	Co-articulation	18 (6)
2b – 2	Fixed	Fast	Tapping	18 (6)
2c – 1	Fixed	Fast	None	20 (13)
2c – 2	Fixed	Slow	None	20 (13)

Note. For experiments with multiple conditions, the same subjects completed all of the tasks.

Table 2

Means (with Standard Deviations) for Reaction Times, Errors, and Time-Out Trials on Anti- and Pro-Press Responses in the Speeded-Task Practice

Exp	Rate	Dual Task	Reaction Time (ms)			Errors			Time Out		
			Anti	Pro	*t*	Anti	Pro	*t*	Anti	Pro	*t*
					Running Memory Span						
1a	fast	none	397 (53)	363 (19)	3.86*	0.83 (1.1)	0.79 (0.9)	< 1.0	0.25 (0.5)	0.17 (0.4)	1.16
1b	slow	none	445 (69)	403 (72)	3.63*	0.50 (0.8)	0.44 (0.6)	< 1.0	0.44 (0.7)	0.17 (0.4)	1.54
1c	slow	co-art	451 (102)	404 (102)	3.62*	1.29 (0.9)	1.33 (1.3)	< 1.0	0.99 (1.0)	1.01 (0.8)	< 1.0
	slow	tap	499 (128)	471 (111)	1.49	0.78 (1.0)	0.65 (0.9)	< 1.0	0.92 (0.8)	0.83 (0.6)	< 1.0
1d	fast	co-art	433 (98)	400 (58)	1.71	1.40 (1.2)	1.06 (1.0)	1.37	0.94 (0.2)	0.90 (0.2)	< 1.0
	fast	tap	479 (136)	449 (120)	1.68	1.00 (1.1)	0.89 (0.5)	< 1.0	1.40 (1.6)	1.11 (1.1)	< 1.0
					Fixed-Length List Memory Span						
2a	slow	co-art	411 (62)	370 (41)	1.90	0.44 (.62)	0.39 (0.9)	< 1.0	0.91 (1.1)	0.32 (0.7)	2.37*
	slow	tap	431 (68)	408 (39)	1.49	1.06 (1.4)	0.50 (0.8)	1.46	0.56 (0.6)	0.56 (0.8)	< 1.0
2b	fast	co-art	419 (72)	388 (54)	2.44*	1.28 (1.5)	0.72 (1.0)	2.09*	0.59 (0.7)	0.72 (1.0)	< 1.0
	fast	tap	441 (96)	397 (76)	2.75*	0.89 (1.0)	1.11 (1.1)	< 1.0	0.56 (0.9)	0.44 (0.5)	< 1.0
2c	both	none	381 (49)	351 (36)	2.31*	0.95 (1.0)	0.65 (1.0)	1.06	0.70 (0.7)	0.40 (0.6)	1.67

* $p < .05$, as determined by paired-subjects *t*-tests for the comparison of reaction times, errors, and time outs on the anti- and pro-press speeded tasks.

Note. The speeded task practice was not paired with a memory task, so the practice was the same across the experiments, except for the kind of dual task. “Exp” = experiment. “Anti” and “Pro” = the anti- and pro-press speeded task conditions, respectively. “Co-art” and “Tap” = the co-articulation and knee tapping dual-task conditions, respectively. Reaction times are for correct responses only. Errors (same-side key presses on antipress trials and opposite-side key presses on pro-press trials) refer to the mean number of errors out of 18 trials. *Time Out* here refers to reaction times exceeding 1,000 ms; the mean number of these trials is shown. They were dropped from the analysis, and the computer program re-ran these trials.

Table 3

Means (with Standard Deviations) for Reaction Times, Errors, and Time-Out Trials on Anti- and Pro-Press Responses in the Speeded Task, When Performed With a Memory Task

Exp	Rate	Dual Task	Reaction Time (ms)			Errors			Time Out		
			Anti	Pro	*t*	Anti	Pro	*t*	Anti	Pro	*t*
Running Memory Span											
1a	fast	none	382 (45)	364 (30)	2.10*	4.33 (3.0)	1.83 (2.3)	4.40*	2.83 (0.5)	2.17 (1.8)	< 1.0
1b	slow	none	384 (61)	377 (51)	< 1.0	1.67 (1.6)	1.14 (1.3)	1.47	3.05 (2.2)	3.48 (1.7)	< 1.0
1c	slow	co-	393 (68)	372 (50)	2.39*	5.24 (3.5)	4.86 (3.1)	< 1.0	2.52 (1.7)	2.57 (2.0)	< 1.0
	slow	tap	438 (87)	418 (90)	1.16	4.19(2.8)	4.24 (2.3)	< 1.0	3.05 (1.7)	3.43 (1.9)	< 1.0
1d	fast	co-	427 (73)	400 (47)	2.15*	6.78 (5.5)	5.72 (4.2)	1.01	4.00 (4.4)	4.00 (3.3)	< 1.0
	fast	tap	449 (108)	421 (102)	2.26*	5.94 (4.8)	4.00 (2.6)	1.49	3.44 (0.5)	3.17 (1.2)	< 1.0
Fixed-Length List Memory Span											
2a	slow	co-art	406 (59)	389 (66)	< 1.0	5.00 (3.0)	3.44 (2.0)	2.12*	3.44 (2.2)	2.83 (1.7)	< 1.0
	slow	tap	399 (54)	389 (51)	< 1.0	3.33 (2.6)	1.96 (1.4)	< 1.0	3.06 (2.5)	2.33 (1.6)	< 1.0
2b	fast	co-art	383 (63)	362 (43)	1.69	4.72 (3.7)	3.83 (3.9)	< 1.0	3.39 (1.8)	3.11 (2.6)	< 1.0
	fast	tap	390 (64)	364 (55)	3.12*	4.39 (2.7)	4.11 (2.6)	< 1.0	3.17 (2.0)	3.28 (1.7)	< 1.0
2c	fast	none	351 (25)	341 (34)	1.44	3.10 (3.5)	1.20 (1.7)	2.60*	4.05 (2.8)	1.75 (2.0)	3.81*
	slow	none	366 (24)	345 (26)	6.29*	4.75 (3.7)	3.80 (3.9)	1.25	3.35 (2.5)	2.2 (2.0)	2.60*

* $p < .05$, as determined by paired-subjects *t*-tests for the comparison of reaction times, errors, and time outs on the anti- and pro-press speeded tasks.

Note. “Exp” = experiment. “Anti” and “Pro” = the anti- and pro-press speeded task conditions, respectively. “Co-art” and “Tap” = the co-articulation and knee tapping dual-task conditions, respectively. Reaction times are for correct responses only. Errors (same-side key presses on anti-press trials and opposite-side key presses on pro-press trials) refer to the mean number of errors out of 18 trials. *Time Out* here refers to reaction times exceeding the participant’s speeded-task practice mean plus 1 SD. They were dropped from the analysis, and the computer program re-ran those trials.

Table 4

Analysis of Variance for Repeated-Measures and Subsequent Pair-Wise Comparisons for Effects of the Speeded Task on Running and Fixed-Length List Memory Span

Exp	Rate	Dual Task	ANOVA				Pair-wise comparisons		
			df	df_{error}	*F*	*MSE*	cont-anti	cont-pro	anti-pro
Running Memory Span									
1a	fast	none	2	46	7.11*	.03	.46* (.13)	.11 (.11)	.34* (.13)
1b	slow	none	2	40	1.41	.83	.32 (.22)	.46 (.25)	.14 (.36)
1c	slow	co-art	2	40	3.80*	.38	.48* (.19)	.42* (.23)	.06 (.14)
	slow	tap	2	40	5.84*	.42	.68* (.20)	.26 (.24)	.42* (.16)
1d	fast	co-art	2	34	3.72*	.16	.31* (.15)	.37* (.14)	.06 (.11)
	fast	tap	2	34	6.46*	.14	.41* (.14)	.36* (.11)	.05 (.12)
Fixed-Length List Memory Span									
2a	slow	co-art	2	34	6.03*	.66	.94* (.33)	.50* (.15)	.44* (.30)
	slow	tap	2	34	2.47	.21	.30 (.19)	.28 (.15)	.02 (.11)
2b	fast	co-art	2	34	12.42*	.20	.68* (.17)	.54* (.14)	.14 (.12)
	fast	tap	2	34	3.57*	.24	.43* (.16)	.28* (.14)	.14 (.14)
2c	fast	none	2	38	6.60*	.14	.39* (.13)	.33* (.12)	.06 (.10)
	slow	none	2	38	2.26	.12	.26 (.11)	.21 (.12)	.06 (.09)

* $p < .05$. Standard deviations in parentheses.

Note. "Exp" = experiment. "Anti", "Pro", and "Cont" = the anti-press, pro-press, and speeded-task control condition, respectively. "Co-art" and "Tap" = the co-articulation and knee tapping dual-task conditions, respectively.