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Interfering with free recall of words: Detrimental effects of phonological competition

Myra A. Fernandes [a,*], Jeffrey D. Wammes [a], Sandra Priselac [b], Morris Moscovitch [c,d]

[a] Department of Psychology, University of Waterloo, Waterloo, Ontario, Canada
[b] Baycrest Centre for Geriatric Care, Toronto, Ontario, Canada
[c] Rotman Research Institute, Baycrest, Toronto, Ontario, Canada
[d] Department of Psychology, University of Toronto, Toronto, Canada

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ABSTRACT

We examined the effect of different distracting tasks, performed concurrently during memory retrieval, on recall of a list of words. By manipulating the type of material and processing (semantic, orthographic, and phonological) required in the distracting task, and comparing the magnitude of memory interference produced, we aimed to infer the kind of representation upon which retrieval of words depends. In Experiment 1, identifying odd digits concurrently during free recall disrupted memory, relative to a full attention condition, when the numbers were presented orthographically (e.g. nineteen), but not numerically (e.g. 19). In Experiment 2, a distracting task that required phonological-based decisions to either word or picture material produced large, but equivalent effects on recall of words. In Experiment 3, phonological-based decisions to pictures in a distracting task disrupted recall more than when the same pictures required semantically-based size estimations. In Experiment 4, a distracting task that required syllable decisions to line drawings interfered significantly with recall, while an equally difficult semantically-based color-decision task about the same line drawings, did not. Together, these experiments demonstrate that the degree of memory interference experienced during recall of words depends primarily on whether the distracting task competes for phonological representations or processes, and less on competition for semantic or orthographic or material-specific representations or processes.

1. Introduction

The degree to which we can multi-task provides a window on the capacities and limitations of human memory abilities. In this study we examine which property, and type of processing of items in a distracting task performed concurrently during retrieval, influenced the magnitude of interference on free recall of a list of words. We presumed that the magnitude of interference with memory, specifically free recall of words, depends on the demands of the chosen distracting task, and whether these coincide with those needed for the memory retrieval task. This logic has been applied in past studies to better understand the component processes critical for the encoding versus retrieval phase of memory.

Specifically, divided attention (DA) during encoding has been shown to produce substantial decrements to memory performance (Anderson et al., 1998; Baddeley et al., 1984; Craik et al., 1996; Fernandes and Moscovitch, 2000; Guez and Naveh-Benjamin, 2006; 2013; Naveh-Benjamin et al., 1998, 2006), regardless of the type and processing requirements of the distracting task that is concurrently performed. Such a finding has led researchers to conclude DA leads to a marked reduction in general processing resources needed for elaboration and organization of information, known to promote successful encoding; as a result, memory suffers significantly and reliably when attention is divided at encoding.

On the other hand, the effects of DA at retrieval appear to be more nuanced and variable. Similar to encoding, the effects of DA at retrieval *can* be large, particularly when the memory task is one that can benefit from strategic processing such as chunking or organization, that are presumed to be dependent on the prefrontal cortex (PFC). Such tests include recall of categorized word lists (Moscovitch, 1994; Park et al., 1989; Stuss et al., 1994), list discrimination (Dywan and Jacoby, 1990; Jacoby, 1991), release from proactive inhibition (Moscovitch, 1989, 1994), or tasks that engage elaborative encoding or contextual recollective retrieval (Hicks and Marsh, 2000; Lozito and Mulligan, 2006; Skinner and Fernandes, in press). Large interference effects on retrieval have also been observed when the centrally-demanding response selection phase for each concurrent task is manipulated (Rohrer and Pashler, 2003).

* Correspondence to: Department of Psychology, University of Waterloo 200 University Ave W Waterloo, ON, N2L 3G1 Canada.
E-mail address: mafernan@uwaterloo.ca (M.A. Fernandes).

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By contrast, when the memory test consists of free and cued recall of unrelated lists of words, or does not require retrieval of contextual or source information, several studies have shown that effects of DA at retrieval are minimal, at least when the materials used in the distracting and memory tasks are dissimilar (Anderson et al., 1998; Baddeley et al., 1984; Craik et al., 1996; Fernandes and Moscovitch, 2000; Guez and Naveh-Benjamin, 2006; 2013; Naveh-Benjamin et al., 1998). In these cases, memory may rely more on direct associative processes mediated primarily by the medial temporal lobe/hippocampus (MTL/H) than on strategic processes mediated by the frontal lobes (Moscovitch, 1994). However, substantial effects of DA at retrieval have been found when there was overlap between the material used in the memory and the concurrent task. For example, Fernandes and Moscovitch (2000) showed that recall of a list of unrelated words decreased by 30% from full attention levels during DA with a word-monitoring distracting task, but only decreased 13% when the distracting task was an equally demanding digit-monitoring one. This pattern of DA effects at retrieval was interpreted as arising from competition between the word-based distracting task and the verbal memory test for a common representational system during recovery of the memory trace, and to a negligible extent on competition for general resources. Such a *material-specific account* (Fernandes and Moscovitch, 2000) was similar to that invoked to explain interference on short-term memory retrieval tasks, performed under dual-task conditions (Pellegrino et al., 1976a; 1976b). Material-specific interference has since been replicated several times in long-term memory paradigms (Barnes and Dougherty, 2007; Ciaramelli et al., 2009; Clarke and Butler, 2008; Fernandes and Moscovitch, 2000; 2002; 2003; Fernandes et al., 2004; Fernandes, Moscovitch et al., 2005, 2006; Wais et al., 2010, 2012 but see Hicks and Marsh (2000); Knott and Dewhurst, 2007).

Subsequent work sought to further specify these effects by exploring whether, in addition to material-specific interference, the processing requirements of the materials played a role in influencing the magnitude of interference. Thus, distracting tasks requiring different processing types were contrasted while holding the materials, or representational system for each task, constant. Fernandes and Guild (2009) tested participants' recognition memory for either words or visuo-spatial patterns. During retrieval, attention was divided between this primary memory task, and a distracting task that required phonological, or visuo-spatial decisions to letters. An interaction was found such that the visuo-spatial distracting task produced more interference with retrieval of visuo-spatial grids than did the phonological task, whereas the opposite was true when the target retrieval information was words. This interaction is consistent with the possibility that similarity in processing requirements across target and distracting tasks plays a role in mediating the magnitude of retrieval interference. Support for this idea was also found in our other work in which memory for Chinese characters, under DA at retrieval, suffered more interference from a visuo-spatial than a phonological distracting task (Fernandes et al., 2013), and in a related study in which memory for upright or inverted faces was differentially hampered depending on whether the distracting task engaged configural or featural processing, respectively (Wammes and Fernandes, 2015). Together, these findings implicate processing requirements in determining susceptibility to dual-task interference.

Determining the nature of these nuanced DA effects on memory can offer insight into the code used for retrieving words from memory. For example, there is reliable evidence that on immediate tests of memory, phonological loop operations are disrupted when to-be-remembered items are phonologically similar than dissimilar (Conrad and Hull, 1964; Baddeley, 1966), and when a distracting task incorporates phonological processing as in studies showing negative effects of articulatory suppression on short-term memory (Alloway et al., 2010; Toppino and Pisegna, 2005). Current theories suggest that information held in short-term memory consists of activated items represented in long-term memory (Cowan, 1999, 2005; Ruchkin et al., 2003). In addition, other models suggest that items retrieved from long-term memory are held in short-term memory while awaiting a response or during other operations (Baddeley, 2007). Based on findings showing interference from concurrent phonological tasks on STM for words (e.g. Pellegrino et al., 1967a), both views predict that similar concurrent interference effects would be found during retrieval from long-term memory in a free recall task. In the current study, we aimed to pinpoint the specific locus of disruption to long-term memory for a list of words, by comparing the magnitude of interference effects produced by various distracting tasks performed concurrently at retrieval.

Our predictions for the experiments reported here are derived from a neuropsychological model of memory proposed initially by Moscovitch and Umiltà (1991; Moscovitch, 1994). Here we aim to specify further the components involved in retrieval. According to that model, retrieval requires two main types of components. The first, mediated by the pre-frontal cortex (PFC), is needed to maintain retrieval mode, to implement strategic aspects of retrieval search and monitoring, and to coordinate competing task demands. The second component, believed to be mediated by the medial temporal lobe/hippocampus, involves the relatively automatic re-activation of memory traces resulting from their interaction with memory cues, a process termed ecphory by Semon (1924) (see also Schacter et al. (1978)). This model suggests that the ecphoric process requires little if any resources, and would not be affected by DA unless the task material, or type of processing necessary for free recall, in this case orthography, phonology, and semantics, is required in the distracting task as well. That is, according to the model, DA is believed to exert its effect by disrupting the neocortical representations that constitute the memory trace for studied words, and by hampering the processes necessary to maintain or activate those representations.

In Experiment 1, we examined the orthographic contribution to interference by comparing the size of memory interference, on free recall of words, from a distracting task requiring odd-digit decisions to numbers presented orthographically (e.g. 12), or numerically (e.g. 12). In Experiment 2, we compared the size of memory interference, on free recall of words, produced by distracting tasks that required phonological decisions to words, which also have an orthographic component, and to pictures, which do not. In Experiment 3 we examined interference from a non-orthographic (picture) distracting task, when the type of processing required either phonological or semantic processing, and compared the magnitude of memory interference from each. Finally, in Experiment 4, we compared the magnitude of interference from two picture distracting tasks that were matched pre-experimentally in terms of difficulty level, which engaged either phonological or semantically-based classification decisions.

1.1. *Experiment 1*

In our previous work (Fernandes and Moscovitch, 2002), participants were required to make semantic judgments (is the object bigger or smaller than a computer monitor) to pictures (from Snodgrass and Vanderwort, 1980) while concurrently recalling words. Memory interference in this condition was significantly smaller than that produced by a word-based distracting task in which the items were pronounceable non-words, with no semantic component, and required only phonological judgments. While suggesting a lesser role for semantic or visual competition, the aforementioned study did not attempt to identify whether it was orthography or phonology, in the distracting task, which produced the large effect on memory retrieval, leaving some uncertainty as to the locus of the interference.To address this uncertainty, recall of a list of unrelated words was measured under dual-task conditions, in order to determine the contribution of orthography to memory for words. To do so, the magnitude of interference produced by a distracting task that required differentiating odd from even numbers presented orthographically (e.g. 19) was contrasted with the same numbers presented numerically (e.g. 19). If orthography is critical in mediating interference with verbal memory, one might expect larger interference effects in the former condition, relative to the latter. Further, if the orthographic presentation led to greater interference, this finding would support the notion that the non-semantic aspects of the distracting task are important in determining the level of interference (Fernandes and Moscovitch, 2002). This would be especially compelling given that the two tasks are semantically equivalent (i.e. the numbers, and the decisions are the same). Moreover, if, contrary to our central thesis, semantic competition was most responsible for dual-task interference, neither task should lead to dual-task interference, as there is no semantic overlap between items on the distracting task and the memory task.

2. Method

2.1. Participants

Participants were 24[1] undergraduate students (13 female) with a mean age of 21.3 years (SD=6.0), studying at the University of Toronto at Mississauga, who received course credit for their participation. All participants were native English speakers, and had normal or corrected to normal vision and hearing.

2.2 Materials

2.2.1. Memory task. Stimuli for the memory tasks consisted of 64 medium to high frequency (20–100 occurrences per million; Francis and Kucera, 1982) common nouns, containing two syllables and a mean of 6 letters. Words were recorded in a sound proof-booth onto an audio file via a MacIntosh computer using the Sound Designer II program (Avid Software, Palo Alto, California). Four word lists were created by randomly choosing 16 words for each list from the pool of 64 words, with 3 s of silence inserted between words. The lists were then recorded onto an audiotape and presented via a cassette-player.

2.2.2. Distracting tasks. Stimuli for both of these tasks consisted of two-digit numbers that differed in mode of presentation. In the ‘print-digits’ task, numbers were presented orthographically (e.g. 22), and in the ‘numerical-digits’ task, numbers were presented in Arabic numerals (e.g. 22). For each, three 50-item lists were created such that in each, half of the numbers were odd and the other half even. One list was used for practice, one for a single-task measure and the third for the DA condition with recall. Also for each task, a shorter, 20-item list was created, and used as a filler task (counterbalanced across participants) in the full attention (FA) condition prior to recall (see procedure).

2.2.3. Procedure. Participants were tested individually, and completed the entire experiment in approximately 1 h. For the memory task, participants were asked to try to commit to memory a list of 16 words, heard at a rate of one word every 4 s, for a later recall test. Following this, participants did an arithmetic task in which they counted backwards by threes from a number heard at the end of the study list, for 15 s, to eliminate recency effects (as in Craik et al., 1996).

Items in the distracting tasks were presented visually on a computer screen at a rate of one item every 2 s. For both tasks, participants indicated if the number was odd by pressing a key with their dominant writing hand. While response times were recorded, accuracy was emphasized. Participants were given a practice block for the memory task, followed by practice on the print-digits, then numerical-digits task. Following practice, single-task performance for one of the distracting tasks was measured, with single-task performance on the other task measured (in counterbalanced order) at the end of the final experimental condition.

Following the first single-task measure, the three experimental conditions (FA plus two DA conditions) were administered, counterbalanced across participants. After the study phase (and arithmetic task) in each experimental condition, and prior to recall, participants performed either the print-digits or numerical-digits task alone (as a filler) for 40 s, until the computer emitted a low-pitched tone, signaling that recall should begin. For the DA conditions, this was done so that participants would be engaged in the distracting task prior to beginning recall. In the FA condition, the filler task ended once the computer signaled that recall of the study words should begin, thereby keeping the time lag between study and recall, as well as the need to perform another task before recall, the same in the DA and FA conditions.

In the two DA conditions, the distracting and free recall tasks were performed simultaneously for 60 s, and the importance of placing 50% of their effort on recall and 50% on the distracting task was emphasized. All recall responses were tape-recorded. Participants were given a four-minute break before beginning the next condition.

3. Results

3.1. Memory task

The print-digits task interfered significantly with memory performance, relative to the FA condition. In contrast, free recall was not affected by the concurrently performed numerical-digits distracting task. The means for each condition are presented in Table 1. There was no difference in the number of words recalled in the FA condition depending on the type of filler task used prior to recall. The data were analyzed in a two between-(order of experimental condition and order of single-task measure for the distracting tasks) and one within-subjects (experimental condition) ANOVA. Preliminary analyses indicated that there were no significant main effects or interactions with the order factors on free recall performance.

There was a main effect of experimental condition $F(2, 46)=4.95$, $MSE=2.76$, $p<.05$, $\eta^2=.18$. Significantly fewer words were recalled in the print-digits compared to FA condition, $F(1, 23)=9.27$, $MSE=5.83$, $p<.01$, $\eta^2=.19$. The difference in words recalled in the numerical-digits and FA condition was non-significant, F(1,

[1] It was decided, pre-experimentally, to exclude participants who fewer than 4 words under full attention conditions. Recalling fewer than 4 words under FA could make comparisons with DA conditions problematic as recalling even 1 word less under DA conditions would indicate a significant decline in memory. As well, based on our previous work, recalling 4 (or less) of 16 words under FA indicates performance almost two standard units of deviation below the mean. This resulted in the exclusion of data from three participants. Additional participants were tested in their place.

Table 1
Number of words recalled in each experiment.

Experiment and Condition	M	SD
Experiment 1		
Full Attention	7.80	2.24
DA print-digits	6.30	2.19
DA numerical-digits	7.17	2.20
Experiment 2		
Full Attention	10.16	2.73
DA picture-syllable	7.50	1.87
DA word-syllable	7.58	2.19
Experiment 3		
Full Attention	8.43	2.48
DA picture-syllable	6.24	2.76
DA picture-size	7.43	2.91
Experiment 4		
Full Attention	7.48	2.88
DA picture-phonology	5.57	2.63
DA picture-visual	6.52	3.50

Note: DA=divided attention.

23)=1.83, $p > .05$, $\eta^2 = .07$, *ns*. While fewer words were recalled in print-digits than in the numerical-digits DA condition, the difference only approached significance, $F(1, 23) = 3.29$, $MSE = 5.59$, $p = .08$, $\eta^2 = .08$, *ns*. We calculated the percentage decline ((FA–DA)/FA) individually for each participant, and then calculated the mean; we found a nominally larger effect in the print-digits compared to numerical-digits DA condition, $F(1,23) = 2.78$, $MSE = .06$, $p = .10$, $\eta^2 = .11$, *ns*.

3.2. Distracting tasks

Accuracy rates (calculated as hit rate minus false alarm rate) on the distracting tasks under DA conditions were worse than single-task performance. There were no significant main effects or interactions with the order factors. The data were analyzed in a 2 × 2 ANOVA, with Attention (full and divided) and Task (print-digits and numerical-digits) as within subject factors. The mean accuracy rates for each task, in each condition, are presented in Table 2. There was a main effect of Attention $F(1, 23) = 43.76$, $MSE = .02$, $p < .001$, $\eta^2 = .66$, with poorer performance under DA than single-task conditions. The effect of Task approached significance, $F(1, 23) = 4.00$, $MSE = .01$, $p = .06$, $\eta^2 = .15$, with poorer performance in the print-digits than numerical digits condition. Importantly, however, the Attention × Task interaction was also not significant $F(1, 23) = .004$, $MSE = .008$, $p = .95$, $\eta^2 = .00$, and in line with this, when we calculated the percentage decline in accuracy rate, from single to dual-task conditions, it did not differ across the distracting tasks $F(1, 23) = .02$, $MSE = .02$, $p = .89$, $\eta^2 = .00$, *ns*.

Reaction time (RT) data for correct responses on each distracting task were analyzed in a 2 × 2 ANOVA, with Attention and Task as within-subject factors. There were no significant main effects or interactions with the order factors. The mean RT for correct responses on each distracting task, in each condition, is presented in Table 3. There was a main effect of Attention $F(1, 23) = 42.31$, $MSE = 10{,}078.11$, $p < .001$, $\eta^2 = .65$, and Task, $F(1, 23) = 48.90$, $MSE = 15{,}276$, $p < .001$, $\eta^2 = .68$, with slower RTs overall in the DA conditions, and on the print-digits task. As with distracting task accuracy data, the Attention × Task interaction was not significant, $F(1, 23) = .006$, $MSE = 5609$, $p = .94$, $\eta^2 = .00$.

Table 2
Accuracy rate on distracting tasks in each condition and experiment.

Experiment and Condition	M	SD
Experiment 1		
Baseline print-digits	.88	.09
DA print-digits	.71	.18
Baseline numerical digits	.92	.05
DA numerical-digits	.75	.14
Experiment 2		
Baseline picture-syllable	.53	.19
DA picture-syllable	.39	.22
Baseline word-syllable	.70	.07
DA word-syllable	.52	.12
Experiment 3		
Baseline picture-syllable	.51	.22
DA picture-syllable	.31	.25
Baseline picture-size	.89	.12
DA picture-size	.68	.21
Experiment 4		
Baseline picture-phonology	.73	.20
DA picture-phonology	.43	.25
Baseline picture-visual	.64	.17
DA picture-visual	.41	.24

Note: DA=divided attention.

Table 3
Reaction time on distracting tasks in each condition and experiment.

Experiment and condition	M	SD
Experiment 1		
Baseline print-digits	848	150
DA print-digits	982	148
Baseline numerical digits	672	154
DA numerical-digits	805	173
Experiment 2		
Baseline picture-syllable	1062	113
DA picture-syllable	1082	95
Baseline word-syllable	870	124
DA word-syllable	953	104
Experiment 3		
Baseline picture-syllable	1184	201
DA picture-syllable	1195	246
Baseline picture-size	813	140
DA picture-size	931	158
Experiment 4		
Baseline picture-phonology	1235	152
DA picture-phonology	1191	229
Baseline picture-visual	997	140
DA picture-visual	1076	229

Note: DA=divided attention.

4. Discussion

Results indicate that processing digits presented in print form (i.e. orthographically), but not in numerical form, in a distracting task, disrupts free recall relative to FA performance. The existence of a significant decrement in memory in the print-digit DA condition argues against the interpretation that competition between the distracting and memory tasks is for semantic representations since there is no semantic overlap between the memory test and the distracting task. Though significant, the magnitude of interference in the print-digits condition was smaller than that found in other studies that used word-based distracting tasks (Fernandes and Moscovitch, 2000, 2002, 2003). One reason for the smaller interference effect may be that numbers, even when presented in print form, activate a numerical representation automatically (Ischebeck, 2003), thereby reducing competition with the words in memory for orthographic or phonemic representations. This would also explain why the difference between the print and numerical condition, though evident, only approached significance.

Although analysis of distracting task RT indicates significantly slower performance in the print-digits than numerical-digits condition, and accuracy shows a similar trend, we do not believe this can account for the difference in magnitude of memory interference from each; looking at distracting task performance, there was no Task × Attention interaction on either accuracy or RT, which would be expected if one of the tasks was more attention-demanding. Nonetheless, we consider this alternative hypothesis more fully in Experiment 3 and in the General Discussion.

4.1. Experiment 2

Experiment 1 demonstrated that processing numbers presented in print (word) format, in a distracting task during retrieval, produced significant interference with memory for words. However, that experiment does not test directly whether it was orthography or phonology that was the locus of the effect. It is possible that interference may have arisen because of the close affinity between orthography and phonology (i.e. viewing words activates phonology automatically, and it is the latter component that mediates the effect). In order to explore this distinction explicitly, the next experiment examined whether a distracting task that demanded phonological processing would interfere with retrieval, even when the presented stimuli themselves had no orthographic component.

If competition for phonological processes mediates interference with retrieval of words, then the magnitude of memory interference should be the same regardless of whether the distracting task material consists of pictures, non-words, or words, as long as phonological processing is required; such a finding would suggest that, in line with recent findings (Fernandes and Guild, 2009; Fernandes et al., 2013; Fernandes and Wammes, 2015), it is the processing requirements in the distracting task (rather than material per se) that determine the magnitude of memory interference at retrieval. The present experiment tested this hypothesis. We compared the magnitude of memory interference resulting from two distracting tasks which each required phonological processing. In both cases, participants were asked to make decisions about the number of syllables in the name of an item. Critically, in one case, these decisions were made with respect to the names of line drawings retrieved from Snodgrass and Vanderwort (1980). In the other case, the decisions were made in response to written words.

If competition for orthographic representations is the source of memory interference, then the interference effect should be diminished or absent in the picture-syllable, relative to the word-syllable DA condition. If, however, competition for phonological representations or processes is critical, then the presence (words) or absence (pictures) of orthographic information in the distracting tasks should matter little, and large memory interference should be observed from both distracting tasks.

5. Method

5.1. Participants

Participants were 24 naive undergraduate students (17 female) with a mean age of 19.5 years (SD=.9), studying at the University of Toronto's downtown campus, who received course credit for their participation. All participants were native English speakers, and had normal or corrected to normal vision and hearing.

5.2. Materials

5.2.1. Distracting tasks. For the word-based task, three 50-item word lists were created from a pool of 170 medium to high frequency words (20–100 occurrences per million; Francis and Kucera, 1982); 40% of the words had 2 syllables, and the rest had 1 or 3 syllables. One list was used for practice, one for a single-task measure and the third for the DA condition with recall. A shorter, 20-item word list was also created, and used as the filler task for half of the participants in the FA condition prior to recall (see procedure). Each list consisted of one, two and three syllable words.

Stimuli for the picture-based task consisted of 170 black line drawings (from Snodgrass and Vanderwort, 1980) presented on a white background, as well as line drawings drawn by a colleague, which were easily identifiable to participants in a pilot study[2]. Each picture was 170 × 170 pixels in size. Three 50-item picture lists, and one 20-item picture list, were created such that approximately 40% of the verbal labels for the pictures had two syllables, and the rest had one or three syllables.

5.2.2. Procedure. The procedure was identical to that described in Experiment 1 except that the print-digit and numerical-digit tasks were replaced by the word- and picture-syllable distracting tasks, in which participants made a key press if the item had two syllables.

6. Results

6.1. Memory task

Free recall under DA conditions was disrupted significantly compared to FA, regardless of whether the distracting task items were pictures or words. The means for each condition are presented in Table 1. There was no difference in the number of words recalled in the FA condition depending on the type of filler task used prior to recall. Data were analyzed in the same manner as in Experiment 1. There were no main effects or interactions with the order factors.

There was a main effect of experimental condition $F(2, 46)=18.71$, $MSE=2.95$, $p<.001$, $\eta^2=.45$. Significantly fewer words were recalled in the picture-syllable, $F(1, 23)=25.60$, $MSE=6.67$, $p<.001$, $\eta^2=.53$, and word-syllable, $F(1, 23)=22.49$, $MSE=7.12$, $p<.001$, $\eta^2=.49$, DA conditions compared to the FA condition. The mean number of words recalled in the two DA conditions did not differ significantly, $F(1, 23)=.04$, $MSE=3.91$, $p=.84$, $\eta^2=.00$, *ns*, and the percentage decline in memory (from FA to DA conditions) was similar in the two DA conditions, $F(1, 23)=.02$, $MSE=.02$, $p=.90$, $\eta^2=.00$, *ns*.

[2] Two participants were excluded, as they recalled fewer than 4 words under FA.

6.2. Distracting tasks

Accuracy rates (calculated as hit rate minus false alarm rate) on the distracting tasks under DA conditions, were worse than single-task performance. There were no significant main effects or interactions with the order factors. Data were analyzed in a 2×2 ANOVA, with Attention (full and divided) and Task (picture-syllable and word-syllable) as within-subject factors. The mean accuracy rates for each task, in each condition, are presented in Table 2. There was a main effect of Attention $F(1, 23)=13.55$, $MSE=.03$, $p<.001$, $\eta^2=.37$, and Task, $F(1, 23)=64.95$, $MSE=.01$, $p<.001$, $\eta^2=.74$. Performance was lower overall under DA, and on the picture-syllable task, though the Attention × Task interaction was not significant, $F(1, 23)=.07$, $MSE=.01$, $p=.80$, $\eta^2=.00$. In line with this, the percentage decline in accuracy rate, from single to dual-task conditions, did not differ significantly across distracting tasks, $F(1, 23)=.33$, $MSE=.11$, $p=.57$, $\eta^2=.01$.

RTs for correct responses on each distracting task were analyzed in a 2×2 ANOVA, with Attention and Task as within-subject factors. There were no significant main effects or interactions with the order factors. The mean RT for correct responses on each distracting task, in each condition, is presented in Table 3. There was a main effect of Attention $F(1, 23)=8.55$, $MSE=7556.43$, $p<.01$, $\eta^2=.27$, and Task, $F(1,23)=96.39$, $MSE=6394$, $p<.001$, $\eta^2=.81$ with slower RTs overall in the DA conditions, and on the picture-syllable task. The Attention × Task interaction approached significance, $F(1, 23)=4.19$, $MSE=5726.68$ $p=.052$, $\eta^2=.15$.

7. Discussion

We examined whether a distracting task that required phonological processing would interfere with retrieval, even when the items themselves had no orthographic component. Results indicate that large disruptions to memory occur when a distracting task performed concurrently during retrieval requires phonological processing, at least when we consider memory for words. That is, significant memory interference was found from both a picture- and word-based distracting task. Eliminating orthography, in the case of the DA picture-syllable condition, did not diminish the effect compared to when orthography was retained, as in the DA word-syllable condition.

The current results support our claim that it is the type of processing, rather than material, in the distracting task that influences the size of memory interference. In particular, the results suggest that interference occurs primarily at the phonological, rather than orthographic level. Although accuracy was lower overall in the picture-syllable distracting task, and RT slower, we do not believe this contributed significantly to performance under DA conditions, as again (as in Experiment 1), the Task × Attention interactions for distracting task performance were not significant. In the following two experiments we examine this alternative account directly by considering whether differences in resource-demands of the distracting tasks can account for large memory interference effects.

7.1. Experiment 3

In Experiment 3, we held the type of material in the distracting task constant, and examine how changes in the type of processing of the exact same distracting task material, can alter the size of interference on recall. Specifically, we compared two distracting tasks that each required decisions to line drawings. To manipulate the processing requirements, one task required phonological decisions to line drawings, while the other task required semantically-based spatial decisions of such drawings. Thus, by holding material-type constant, we directly test the hypothesis that the locus of interference at retrieval arises from competition for phonological representations or processes.

In addition, because one might argue that the memory interference effects reported in the study thus far are due to differences in task difficulty rather than processing demands, we explicitly examined the relative resource demands of each of the current experiment's distracting tasks. A subset of participants performed each distracting task simultaneously with an auditory continuous reaction time (CRT) task. In the CRT task, participants identified computer-generated tones as low, medium or high pitched. The RT and number of correct responses on the auditory CRT task were recorded and analyzed as a proxy for how resource-demanding each distracting task was, with longer RTs indicating greater resource demands.

8. Method

8.1. Participants

Participants were 48[2] undergraduate students (23 female) with a mean age of 20.27 (SD=2.03), studying at the University of Waterloo, who received course credit for their participation. All participants were native English speakers, and had normal or corrected to normal vision and hearing.

8.2. Materials

8.2.1. Memory task

Stimuli for the memory tasks were the same as those used in Experiment 1.

8.2.2. Distracting tasks. Stimuli for the picture-based task were the same as in Experiment 2, with the addition of another 50 pictures chosen from the set of black line drawings from Snodgrass and Vanderwort (1980) presented on a white background, as well as line drawings drawn by a colleague, which were easily identifiable to participants in a pilot study.[3] For the picture-syllable task, approximately 40% of the verbal labels for the pictures had two syllables, and the rest had one or three syllables, and for the picture-size task, approximately 40% represented animals or objects which, in the real world, were bigger than a computer monitor.

8.3. Procedure

The procedure was identical to that described in Experiment 1, except that the print-digit and numerical-digit tasks were replaced by the picture-syllable task, in which participants made a keypress when the item, when verbalized, had two syllables, and the picture-size distracting task, in which participants made a keypress when the item, in the real world, was larger than a computer monitor.

8.4. Comparing resource demands of the distracting tasks

We used the auditory CRT task to compare the difficulty, or

[3] To measure consistency in picture naming, 6 pilot subjects were shown a set of 268 pictures and were asked to provide verbal labels for the items. A subset of 170 pictures, with a mean naming agreement of 96.36% was chosen to compose three 50-item picture lists and one 20-item picture list. Naming agreement meant that there was either no difference in the labels assigned to the pictures, or the labels that were provided did not affect the syllabic status of the word. For example, if someone was presented with a picture of a bicycle (3-syllables) and labeled it as 'bike' (1-syllable), the item would still be considered a non-target for 2-syllable identifications.

resource demands, of the picture-syllable and picture-size distracting tasks. A subset of 16 participants completed this task, and identified randomly presented computer-generated tones as low, medium or high in pitch. Participants were told to respond as quickly and as accurately as possible by keypress. The subsequent tone was presented as soon as the participant pressed a key, or after 3 s had elapsed. Each participant completed the CRT alone as a baseline measure, or concurrently with either the syllable or size task. To avoid participants making two different manual responses in the DA conditions, participants responded verbally to the pictures, and the experimenter recorded the participant's responses by pressing a key on a separate keyboard. The RT and number of correct responses in the auditory CRT were recorded and analyzed as a means of gauging the resource demands of each distracting task.

9. Results

9.1. Memory task

Both DA conditions impaired retrieval significantly. Data were analyzed in a two between- (order of experimental condition and order of single-task measure for the distracting tasks) and one within-subjects (condition) ANOVA (see Table 1 for means). Preliminary analyses indicated that there were no significant main effects or interactions with the order factors. Thus, the ANOVA results are reported below, collapsing across order conditions.

There was no difference in the number of words recalled in the FA condition depending on the type of filler task used prior to recall. There was a main effect of experimental condition, $F(2, 90)=18.25$, $MSE=3.05$, $p<.001$, $\eta^2=.29$. Significantly fewer words were recalled in the picture-syllable compared to the FA, $F(1, 45)=37.91$, $MSE=5.85$, $p<.001$, $\eta^2=.46$, and picture-size condition, $F(1, 45)=11.42$, $MSE=5.76$, $p<.01$, $\eta^2=.20$. The difference in words recalled in the picture-size and FA condition was also significant, $F(1, 45)=6.90$, $MSE=6.67$, $p<.0167$, $\eta^2=.13$. In an ANOVA using percentage decline scores (memory interference) for each participant, there was a main effect of DA condition, with significantly larger interference in the picture-syllable than picture-size condition, $F(1, 45)= 9.63$, $MSE=.056$, $p<.01$, $\eta^2=.18$.

9.2. Distracting tasks

Accuracy rates (calculated as hit rate minus false alarm rate) on the distracting tasks under DA conditions were worse than single-task performance. There were no significant main effects or interactions with order. Data were analyzed in a 2×2 ANOVA, with Attention (full and divided) and Task (picture-syllable and picture-size) as within-subject factors. Mean accuracy rates for each task, in each condition, are presented in Table 2. There were main effects of Attention $F(1, 45)=47.32$, $MSE=.042$, $p<.001$, $\eta^2=.51$, and Task, $F(1, 45)=226.07$, $MSE=.03$, $p<.001$, $\eta^2=.83$, such that performance was lower under DA conditions, and on the picture-syllable task. The Attention $\times$ Task interaction was not significant, $F(1, 45)=.08$, $MSE=.032$, $p=.78$, $\eta^2=.00$. In line with the lack of an interaction, the percentage decline in accuracy rate, from single to dual-task conditions, did not differ across tasks, $F(1, 45)=.46$, $MSE=.42$, $p=.50$, $\eta^2=.01$.

RT for correct responses was analyzed in a 2×2 ANOVA, with Attention and Task as within-subject factors. There were no significant main effects or interactions with the order factors. The mean RT for correct responses on each distracting task, in each condition, is presented in Table 3. There were main effects of Attention $F(1, 45)=6.74$, $MSE=27{,}997.16$, $p<.05$, $\eta^2=.13$, and Task, $F(1, 45)=131.65$, $MSE=35{,}277.70$, $p<.001$, $\eta^2=.75$, with slower RTs overall in the DA conditions, and on the picture-syllable task. The Attention $\times$ Task interaction was also significant, $F(1, 45)=5.66$, $MSE=23{,}489.94$, $p<.05$, $\eta^2=.11$.

Table 4
Number of correct responses, and reaction time (in milliseconds) on the auditory continuous reaction time task under single and dual-task conditions in Experiment 3.

Condition	Correct responses M	Correct responses SD	Reaction time M	Reaction time SD
Baseline	105	35	708	178
DA picture-syllable	77	31	1012	247
DA picture-size	56	24	1101	289

Note: DA = divided attention.

9.2.1. Auditory CRT. Due to experimenter error, CRT tone accuracy and RT data for 1 participant were lost, although the accuracy on the distracting task was preserved and included in that analysis.

9.2.2. CRT tone task. We first examined the number of tones identified, then the RT for correct responses (see Table 4 for means). There were no main effects or interactions with the order factor. A within participant ANOVA revealed a main effect of condition $F(2, 28)=20.40$, $MSE=442.61$, $p<.001$, $\eta^2=.59$. Planned comparisons showed the number of tones correctly identified under both dual-task conditions was significantly lower than in the FA baseline condition, $F(1, 14)=10.47$, $MSE=1142.81$, $p<.01$, $\eta^2=.11$, and $F(1, 14)=35.26$, $MSE=1018.62$, $p<.01$, $\eta^2=.72$, for the picture-syllable and picture-size dual-task conditions respectively.

RT. An outlier analysis eliminated RTs greater or lesser than two standard deviations from the mean for each participant in each condition. There were no significant main effects or interactions with the order factor. A within subject ANOVA revealed a main effect of condition $F(2, 28)=38.41$, $MSE=16{,}602.57$, $p<.001$, $\eta^2=.73$. The mean RTs in both the picture-syllable, and picture-size dual-task conditions were significantly longer than in the baseline condition, $F(1, 14)=55.11$, $MSE=25{,}097.67$, $p<.001$, $\eta^2=.80$ and $F(1, 14)=64.38$, $MSE=36{,}069.55$, $\eta^2=.82$, $p<.001$, respectively. The difference in RT across the two dual-task conditions did not differ, $F(1, 14)=3.15$, $p=.10$, suggesting the two distracting tasks are comparable in terms of resource demands.

9.2.3. Distracting task accuracy. The accuracy rate (calculated as hit rate minus false alarm rate) on the picture-syllable task ($M=.33$, $SD=.14$) was significantly worse than on the picture-size task ($M=.57$, $SD=.11$) under dual-task conditions with the CRT task, $t(15)=-7.59$, $p<.001$.

10. Discussion

Once again we showed that even when the material in the distracting task is dissimilar from that in the memory task, large memory interference can be observed. The critical feature of distracting task items, therefore, cannot be similarity in material. Instead, results are consistent with the claim, throughout the study, that competition for phonological processing (required in the concurrent tasks) is the key factor determining the size of memory interference during recall of words. We found that presenting pictures in a distracting task, during retrieval of words, has a disruptive effect on memory that is significantly larger when phonological compared to semantic (spatial) processing of pictures is required.

One might argue that the pattern of memory interference is due to relative differences in resource demands of each distracting task. Analysis of auditory CRT data, however, did not indicate a *consistent* difference in resource demands between the picture-syllable and picture-size distracting tasks. That is, distracting task accuracy under DA with the CRT task was worse on the picture-syllable than picture-size task, but more tones were identified in the picture-syllable than picture-size task. Given that RT is likely a more sensitive measure of resource demands, we compared RT to identify tones across DA conditions and found no significant difference depending on whether the concurrent task was picture-syllable or picture-size. However, the consistent accuracy differences (in Experiment 3 and the CRT) leave open the possibility that the syllable-based distracting task was simply more difficult than the size-based one, and this was driving the memory interference effects. While it would be difficult to remedy this account with the cross-experiment consistency of our findings suggesting processing-specific competition, Experiment 4 sought to address this concern directly. We piloted several distracting tasks, pre-experimentally, and chose to compare effects on memory from two that were relatively well-matched in terms of accuracy, and RT demands.

10.1. *Experiment 4*

While Experiment 3 provides compelling evidence that phonology, more than orthography or semantically-based visual processing of the item in the distracting task, is the key factor influencing the magnitude of DA effects during retrieval of words, Experiment 4 sought to rule out a few possible confounds. First, some aspects of the data indicate that the phonological distracting task may have been more difficult than the picture size-decision one: participants were substantially slower and less accurate on the syllable than size task. Second, participants had to decide whether an item had two syllables, when some contained one or three syllables. Thus, the decision for the phonology-based task required ruling out more possible options than did the size-based task that instead required only a dichotomous decision. Third, the syllable decision requires an intermediate step, in order to translate from an image to its verbal label, before identifying the number of syllables. The size decision also required an intermediate step, to imagine the real size of the object, though arguably this might have been a less resource-demanding step. Accordingly, in Experiment 4 it was our aim not only to conceptually replicate the findings demonstrated in Experiments 1 through 3, but also to rule out these potential confounds. While Experiment 3 addressed the issue of differences in task difficulty by employing a CRT task to compare relative task demands, Experiment 4 takes on this issue more directly by evaluating the level of difficulty, pre-experimentally, of several possible distracting tasks in a pilot phase.

Pre-experimentally, six possible distracting tasks were developed, each requiring dichotomous (yes or no) decisions to a set of Snodgrass images, and each requiring an intermediate step to transition from the stimulus image to the decision. Three of these tasks were designed to require phonological processing, while the other three were designed to engage perceptual processing. All tasks required a ‘yes’ or ‘no’ decision to a specified question, and instructions were included for each that elaborated how to answer, and included examples that would require ‘yes’ versus ‘no’ responses. In a pilot study, twenty-one participants completed all 6 tasks in counterbalanced order. Following this, we selected the pair of distracting tasks (one phonological, the other perceptual) that was most closely matched in terms of accuracy and RT demands (see Table 5). Then in the experimental phase of Experiment 4, we again tested the hypothesis that interference from DA at retrieval is influenced primarily by competition for phonological representations, this time overtly controlling for potential differences in level of difficulty across distracting tasks, while manipulating the type of processing required.

Table 5
Accuracy rate and reaction time on distracting tasks completed pre-experimentally in Experiment 4.

Task	Distracting task decision	Accuracy	RT
Corners^{PR}	Does the object have corners?	.73 (.12)	934.96 (120.53)
Size^{PR}	Is the object bigger than a computer monitor?	.77 (.19)	859.43 (126.03)
Color^{PR}	Is the color of the object a warm color?	.68 (.09)	1018.47 (113.87)
Syllable^{pH}	Is the name of the object two syllables?	.70 (.09)	1222.40 (104.34)
Vowel^{pH}	Does the name of the object contain an'uh' sound?	.55 (.09)	1374.00 (126.25)
Sound^{pH}	Does the name of the object contain a hard sound?	.54 (.09)	1201.19 (124.40)

Note: distracting tasks selected for inclusion in Experiment 4 are denoted in bold; ^{pH}=phonological, ^{PR}=perceptual

11. Method

11.1. *Participants*

Participants were 58[4] undergraduate students (32 female) with a mean age of 21.04 (SD=2.06), studying at the University of Waterloo, who received course credit for their participation. All participants were native English speakers, and had normal or corrected to normal vision and hearing.

11.2. *Materials*

11.2.1. Memory task. Stimuli for the memory tasks were the same as those used in Experiment 1.

11.2.2. Distracting tasks. Stimuli for these picture-based tasks were a set of black line drawings, selected from the International Picture Naming Project (IPNP) (Szekley et al., 2004), which draws from various sources, including the Snodgrass and Vanderwort (1980) black line drawings. For the picture-phonology task, the list of images contained exactly 40% with verbal labels that had two syllables, and the rest had one syllable. For the picture-visual task, exactly 40% represented animals or objects which, in the real world, were judged as having a warm color (e.g. reds and oranges).

11.3. *Procedure*

The procedure was identical to that described in Experiment 3, except that the picture-syllable and picture-size tasks were replaced by the picture-phonology task, in which participants made a keypress to indicate that an item's label, when verbalized, had two syllables, and the picture-visual distracting task, in which participants made a keypress when the item, in the real world, was judged to have a warm color. Specific instructions were given to participants to clarify how to make syllable decisions, and to clarify that “warm colors are the yellows and reds of the color spectrum, associated with fire, heat, sun, and warmer temperatures.” Item analysis of pilot data indicated that participants successfully classified two-syllable items with 72% accuracy (SD=15), and one-syllable items with 69% accuracy (SD=11). Participants also successfully classified ‘warm’ objects as warm with 63% accuracy (SD=25), and ‘cool’ objects as cool with 71% accuracy (SD=12). When dividing items into baseline and DA lists, these

[4] Eight participants were excluded, as they recalled fewer than 4 words in the FA condition making comparisons with DA performance less reliable. An additional 4 participants' data were excluded, as they misunderstood distracting task instructions (e.g. near chance performance; performing the syllable task when they were instructed to perform the color task). Replacement participants were run to achieve the same number of participants as in Experiment 3.

parameters were preserved, such that each list had the same mean identification rate, as indicated by pilot data.

12. Results

12.1. Memory task

Recall in the DA condition with the picture-phonology task was significantly impaired relative to the FA condition. In contrast, free recall under DA did not differ from FA when the distracting task was the picture-visual one. Data were analyzed in a two between-(order of experimental condition and order of single-task measure for the distracting tasks) and one within-subjects (condition) ANOVA (see Table 1 for means). Preliminary results indicated a significant Order × Condition interaction, $F(2, 10)=3.95$, $MSE=3.48$, $p<.001$, $\eta^2=.37$. Upon splitting the data into each of the possible orders, it was determined that the interaction was driven by a null effect of condition in one order wherein the FA condition was performed last, F (2, 12)=.03, $MSE=7.36$, $p=.97$, $\eta^2=.00$, and only a marginal effect in the other order when FA was the final condition, $F(2, 12)=3.72$, $MSE=3.74$, $p=.055$, $\eta^2=.38$. Below we report the ANOVA results, including all participants, collapsing across order conditions. We note, however, that the pattern of ANOVA results reported below were comparable when the aforementioned order factor was included.

There was a main effect of experimental condition $F(2, 90)=9.36$, $MSE=4.49$, $p<.001$, $\eta^2=.17$. Significantly fewer words were recalled in the DA-phonology compared to the FA condition, $F(1, 45)=24.15$, $MSE = 6.97$, $p<.001$, $\eta^2=.35$. The number of words recalled in the DA-visual condition differed significantly from the FA, $F(1, 45)=4.31$, $MSE=4.49$, $p=.044$, $\eta^2=.09$, *ns*, and the DA-phonology conditions, F (1, 45)=4.12, $MSE=10.22$, $p=.048$, $\eta^2=.08$, *ns*. In an ANOVA using percentage decline scores (memory interference) for each participant, there was a main effect of DA condition, with significantly larger interference in the picture-phonology than picture-visual DA condition, $F(1, 45)=4.11$, $MSE=.09$, $p<.05$, $\eta^2=.08$.

12.2. Distracting tasks

Accuracy rates (calculated as hit rate minus false alarm rate) on the distracting tasks were analyzed in a 2 × 2 ANOVA, with Attention (full and divided) and Task (picture-syllable and picture-size) as within-subject factors. Mean accuracy rates for each task, in each condition, are presented in Table 2. There was a main effect of Attention $F(1, 45)=100.20$, $MSE=.032$, $p<.001$, $\eta^2=.69$, such that performance was lower under DA conditions. The main effect of Task was not significant, $F(1, 45)=2.35$, $MSE=.044$, $p=.13$, $\eta^2=.05$, nor was the Attention × Task interaction, $F(1, 45)=2.35$, $MSE=.026$, $p=.13$, $\eta^2=.05$. In line with the lack of an interaction, the percentage decline in accuracy rate, from single to dual-task conditions, did not differ across tasks, $F(1, 45)=2.92$, $MSE=.158$, $p=.09$, $\eta^2=.06$, *ns*.

RT for correct responses was analyzed in a 2 × 2 ANOVA, with Attention and Task as within-subject factors. The mean RT for correct responses on each distracting task, in each condition, is presented in Table 3. The main effect of Attention was not significant, $F(1, 45)=.48$, $MSE=30{,}563.04$, $p=.48$, $\eta^2=.01$. There was however, a main effect of Task, $F(1, 45)=32.58$, $MSE=43{,}914.47$, $p<.001$, $\eta^2=.42$, with slower RTs overall in the phonology task, and a significant Attention × Task interaction, $F(1, 45)=4.79$, $MSE=36{,}372.53$, $p<.05$, $\eta^2=.10$. Bonferroni corrected paired-samples t tests with thresholds of $p<.025$ (0.05/2) indicated that this interaction was primarily driven by slower RTs under DA conditions with the picture-visual task relative to the baseline (FA) condition, $t(45)=2.50$, $SE=31.76$, $p<.025$, while RT under DA with the picture-phonology task did not show this difference, $t(45)=-1.00$, $SE=43.60$, $p=.32$, *ns*.

13. Discussion

Consistent with our prior Experiments, the current results provided support for the hypothesis that retrieval of words from long-term memory is driven largely by competition for phonological-based resources, and thus most susceptible to interference from distracting tasks that engage these same resources. Similar to Experiment 3, we found that a distracting task that required phonological decisions interfered with recall of a list of words more than did a task requiring semantically-based visual decisions to pictures. With this finding, we have strengthened our claim that interference from DA at retrieval on memory for words, is largely processing-specific, and results primarily from competition for phonological processing resources or representations.

This finding replicates and extends the results from Experiment 3. There we compared distracting task difficulty using a CRT task post-experimentally, whereas here we chose our distracting task by comparing pre-experimentally 6 different distracting tasks, and selected the two that were best matched in terms accuracy, and as closely as possible on response time. We also ensured that both distracting tasks required a decision with only two options (1- or 2-syllables, and warm or cool colors), and that both required an intermediate step in order to arrive at a decision. Despite this, we were still able to show that interference with memory for words, under DA at retrieval, was greater when the concurrent tasks both required phonological processing.

14. General discussion

Across four experiments, our goal was to identify which aspects or components of a distracting task are primarily responsible for disrupting free recall of a list of unrelated words. Such knowledge would help delineate the component processes upon which verbal episodic retrieval depends. We showed clear disruption to recall when the distracting task had orthographic, semantic, or visual components, suggesting that competition for general processing resources can disrupt retrieval. Importantly, however, the results of the current study suggest that interference with memory for a list of words, under DA at retrieval, is driven primarily by competition for phonological representations or processes.

In Experiment 1, processing digits presented in print (i.e. orthographically), but not in numerical form, in a distracting task, disrupted recall relative to FA performance. That the print-digit distracting task disrupted memory argues against the possibility that memory interference is due to competition between concurrent tasks for semantic representations, as there is no semantic overlap between them. Though significant, the memory effect from the print-digit distracting task was smaller than reported in our earlier work (Fernandes and Moscovitch, 2000, 2002, 2003). It is possible that viewing numbers in print form activates phonology to some degree, even though such processing is not crucial in an odd-digit decision task, and that this resulted in the small, but significant, disruption of recall. It may also be that when digits are presented in print form, an intermediate step of phonological coding is required in order to represent the print-digits in numerical-digit form. It is possible that this step is necessary to enable the required odd-even judgments in the distracting task. Whichever the case, it is the phonological processes that are implicated. Experiment 1 was unable to differentiate between the contributions of orthography and phonology. Accordingly, in Experiments 2, and 3, we examined more directly the role of orthography and phonology in mediating memory interference from DA at retrieval.

In Experiment 2, the magnitude of memory interference was equivalent when phonological judgments were required,

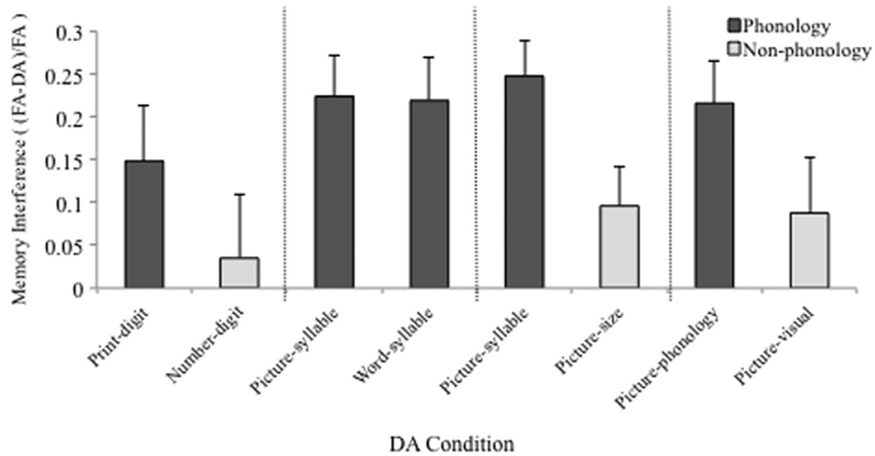

Fig. 1. Memory interference (percentage decline in recall from full attention (FA)) during recall in each divided attention (DA) condition in Experiments 1–4. Error bars represent standard error of the mean.

regardless of whether materials were pictures or words. This finding suggests that orthography in the distracting task is not the main contributor to memory disruption under DA conditions. If it were, memory interference should have been larger in the word-syllable than picture-syllable DA condition. Instead, these data suggest that it is the type of underlying cognitive processing required by the distracting task, rather than the format of presentation (orthography), which modulates the extent of interference at retrieval. Moreover, while Fig. 1 shows that other sources (i.e. orthography in Experiment 1 and semantic and visual processing in Experiments 3 and 4) *can* disrupt memory, they do so to a much lesser degree than phonology.

Nonetheless, it is possible that the picture-syllable task (in Experiment 2) was cognitively more demanding than the word-syllable task, and this, rather than phonological processing demands, accounts for its effect on recall. The results of Experiment 3, however, provide some evidence against the possibility that task difficulty alone can account for large memory interference effects from DA at retrieval. In that experiment, semantic and visual processing of pictures in the distracting task produced less interference than when phonological decisions were required to the same pictures. This pattern occurred despite the fact that the auditory CRT analysis revealed no systematic difference in resource demands, as measured by RT, of these two distracting tasks.

In Experiment 3, however, there were differences in distracting task performance, as measured by accuracy, which could be interpreted as indicating that the phonological-based distracting task was the harder one. Experiment 4 refutes the idea that it was this difference, rather than phonology, that was driving the decline in memory performance under DA conditions with retrieval. In that experiment, a phonological-, and a semantic/visual-based distracting task were matched pre-experimentally with respect to accuracy, as well as RT. Despite this, it was the distracting task that engaged phonological processing that preferentially disrupted memory performance. Taken together, these findings provide compelling evidence that competition for similar processing resources or representations is the underlying factor that most influences memory interference under DA conditions.

Our other published research has shown that it is not the production demands of the retrieval task that lead to memory interference, because such effects are observed even on a recognition test in which verbal (spoken) output is not needed (Fernandes et al., 2005; 2006), and interference occurs regardless of whether the recognition test is presented visually or auditorily. What our past, and current, studies highlight is that it is memory per se, rather than simply output, that is hampered when a distracting task is word-based. The importance, and novelty, of the current study is that it specifies that such interference occurs only when the distracting task requires phonological processing, regardless of material.

According to a dual-coding theory, both visual and verbal representations can be used to represent information (Sternberg, 2003). During a retrieval task, one could theoretically call on either code to support memory (Sternberg, 2003). Our work here suggests that when trying to recall a list of words, there is a heavy reliance on the verbal, specifically, phonological, representation; interference effects are largest when the distracting task forces phonological processing, likely hampering access to phonological representations needed to support the episodic retrieval of the to-be-remembered words.

14.1. Distracting task demands. While it could be argued that the relative difficulty of the distracting tasks contributes to the pattern of data, there are a number of findings in the current work that are difficult to reconcile with such an account. Across the four experiments, accuracy on each distracting task declined under DA. Critically, however, there was no consistently greater effect on distracting tasks that required phonological processing than on those that did not. Although distracting task costs were higher for the picture-syllable conditions, we do not believe this contributed significantly to the interference effect it produced on memory, as large and significant costs were also documented in all other DA conditions, despite the fact that these tasks did not produce memory interference of comparable magnitude (see Fig. 2). This finding adds additional support to our interpretation that interference effects during word retrieval are not determined by the level of difficulty of the distracting task. That performance on our distracting task declined by 18–45% indicates that word retrieval is not automatic, as some have suggested (Baddeley et al., 1984), but is itself resource-demanding, in line with claims from other studies of DA at retrieval (Anderson et al., 1998; Craik et al., 1996; Fernandes and Moscovitch, 2000, 2002, 2003; Johnston et al., 1970; Naveh-Benjamin et al., 1998).

14.2. A revised model of retrieval. The results of the present study are consistent with a neuropsychological model of memory proposed initially by Moscovitch and Umiltà (1991; Moscovitch, 1994), and allow further specification of the components involved in retrieval. Across experiments we observed memory interference to varying degrees for each of the putative processes: minimally for orthography (print-digit distracting task in Experiment 1), somewhat less for semantics and visual processing (picture-size distracting task in

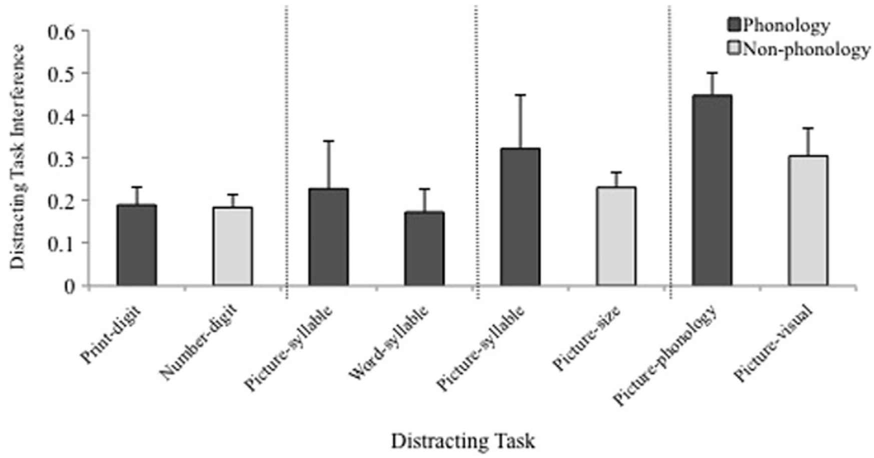

Fig. 2. Distracting task interference (percentage decline in accuracy from single-task conditions) during recall of unrelated word lists, in Experiments 1–4. Error bars represent standard error of the mean.

Experiment 3, picture-visual task in Experiment 4), and a great deal for phonology (syllable distracting tasks in Experiments 2–4). Semantics and orthography caused some memory interference on their own, but did not add to or amplify phonological interference. This suggests that during verbal recall, competition occurs primarily at the phonological level. The alternative explanation, that all processes compete for more general resources (rather than material- or processing-specific representations), is unlikely. If this were the case, we would not have observed the differential effects of DA across different conditions, and the pattern of interference would have been bound to the level of difficulty of each distracting task.

We acknowledge that there is still some question about whether interference is due to competition for memory-related processes (monitoring, search), or competition for (phonological) processes needed to reactivate the word/verbal-based memory trace or to produce it once it is recovered. The aim of our study was to demonstrate that there is indeed a difference in interference across DA conditions, and that this difference cannot be accounted for by material-specific competition. Instead, the series of experiments point to competition for phonological-based representations or processes. This is our central claim. Whether those phonological-based resources are needed to support reactivation of the word/verbal traces, to monitor memory output or search for alternative word targets, or to produce one's task responses verbally, is unclear. That it entails more than interference at a production phase is evident by our previous finding that even when given the opportunity to recall additional material after the interference is over, participants seem unable to do so (Fernandes and Moscovitch, 2000).

One way to compare these alternatives is to conduct an fMRI study to examine differences in activation during retrieval performed concurrently with our distracting tasks from Experiment 3 and/or 4. If competition is for phonological processes needed to reactivate the word's memory trace, then we might expect this to be indexed by activation in left posterior and dorsal frontal gyrus, near the inferior frontal sulcus (BA45) and right inferior frontal gyrus (BA 44) which is typically implicated in representations of phonology (Poldrack et al., 1999). If competition is for phonological processes needed to monitor output or engage in further searches of memory, then we might expect this to be indexed by activation in left dorso-lateral prefrontal cortex which is typically implicated in post-retrieval monitoring (Dobbins et al., 2002).

Our prior study (Fernandes et al., 2005) provided some clues as to the source of general and processing-specific interference under DA. Activity in bilateral dorsolateral PFC (left and right BA 9/46) and left frontal pole (BA 10) did not vary according to whether the distracting task was word-based and led to memory interference, or digit-based and did not. Instead, activity in this region was always higher in any distraction condition relative to FA, suggesting that activation was determined by the total resources needed to coordinate two tasks at the same time. By contrast, activity in other regions seemed to be sensitive to the processing-/material-specific effects of DA on recall. In the left precuneus and inferior frontal region, activity was highest in the most interfering condition, which required processing words. The left precuneus region is closely related to regions needed to represent written and spoken words (McDermott et al., 2003). Therefore, it is expected to be activated more as verbal input from the memory and the distracting task converge on those representations, as compared to conditions in which there is input from only one task. The left inferior frontal cortex, on the other hand, has been implicated in the retrieval and processing of phonological information (Paulesu et al., 1993), particularly during the selection of items from competing or interfering alternatives (Badre et al., 2005). By this account, phonology in a distracting task leads to greater activation in this area because the task requires the same phonological processes as verbal recall, and the selection demands are higher when the two tasks resemble each other. As described in the Attention-to-Memory model (see Cabeza et al., 2008, 2012; Ciaramelli et al., 2008), the dorsolateral PFC mediates the allocation of attention to memory retrieval operations whereas the ventral parietal cortex mediates the bottom-up capture of attention by salient memory contents, sustaining activated representations in the service of thought, planning, action, and in this case retrieval. Examination of each of these regions using fMRI during our DA conditions could help inform which aspect of retrieval under DA is the resource-demanding one, and may also contribute to models of the interaction between working memory and long-term memory (Eriksson et al., 2015).

In contrast, similar interference effects were observed on distracting task performance, in that each task seems to be affected comparably by dual-tasking (see Fig. 2). Such a finding suggests that memory retrieval, though obligatory, is resource-demanding, consistent with the interpretation offered by Craik et al. (1996) to account for similar observations in their study. At retrieval, the memory task takes precedence over the distracting task and draws resources from it.

The neuropsychological, component process model initially proposed by Moscovitch and Umiltà (1991; Moscovitch, 1994), which served as the framework for these studies seems to be generally correct, but its particulars need to be modified in light of evidence presented here. Though the general outlines of the model remains the same, it is clear that further work is needed to refine different aspects of it at both a cognitive and neuropsychological level. In particular more research is needed to determine whether the mechanism leading to memory interference from DA at retrieval is disruption of the memory trace, increased response selection demands, or both. The contribution of the present study is that it shows, behaviourally, that the type of processing required in a distracting task is a major factor leading to disruption in memory retrieval, and by doing so helps identify the component processes that underlie retrieval. We believe it is important to document and specify which DA conditions can hamper long-term memory. In his seminal work, Baddeley (1966) suggested that short-term memory relies on an acoustic representational code, and long-term memory relies more on a semantic code. Our work suggests that retrieval of words from long-term memory is critically dependent on a phonological code, and shows that competition for such a code during retrieval corrupts the memory trace.

While we only tested verbal materials as to-be-remembered information in the current study, our recent work speaks to the generality of this claim in that we have shown processing-specific interference with memory for visuo-spatial information such as faces (Wammes and Fernandes, 2015), Chinese characters (Fernandes et al., 2013), and grid patterns (Fernandes and Guild, 2009), from distracting tasks that require visuo-spatial rather than verbal processing.

15. Conclusions

The present study examined the effect of different distracting tasks, performed concurrently during memory retrieval, on recall of a list of words. By manipulating the type of material and processing required in the distracting task, and comparing the magnitude of memory interference produced, we aimed to infer the kind of representation upon which retrieval of words depends. Across 4 experiments, we demonstrate that the degree of memory interference experienced during recall of words depends primarily on whether the distracting task competes for phonological, and less on competition for semantic, orthographic or material-specific representations or processes.

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