Maintaining task set against distraction: The role of working memory in multitasking

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Acknowledgements:

This research was financed by the Associação Fundo de Incentivo à Pesquisa (AFIP), the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes).

Disclosure statement**:** The authors report no conflicts of interest**.**

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Multitasking, a common feature of everyday life, requires simultaneous maintenance and operation of a range of action-controlling task sets. We attempt to investigate the role of working memory in multitasking by means of the embedded task paradigm. This involves setting up a primary task with a variable task set, which then has to be maintained throughout the performance of a second embedded task with a fixed task set before it can be completed. We test the hypothesis that the capacity to maintain the two task sets so as to avoid mutual interference will depend on working memory. We use Baddeley and Hitch’s multicomponent working memory approach to investigate this. Experiment 1 uses articulatory suppression to examine the potential role of subvocal rehearsal, finding no impact on performance. Experiment 2 uses backward counting to impose an additional executive load, finding a major impact on performance even with the simple task of counting back in ones. This took the form of more pervasive effects of stimulus overlap that could be interpreted in terms of a change in the way the two tasks were managed. The differential impacts of the concurrent tasks indicated that multi-tasking is dependent on working memory, where it draws on limited capacity executive resources, but not on the capacity for temporary phonological storage.

Keywords: task set, multitasking, working memory, binding

# Introduction

Acting upon instructions is an important human capacity, which makes the learning and implementation of new behavior easier and less time consuming. Whether at school, at work, or when participating in psychological experiments, our actions are frequently regulated by verbal instructions. However, little is known about how these are prepared and implemented.

The process of transforming instructions into action demands the organization of relevant rules, facts, and requirements into an effective ‘mental program’ (Duncan et al., 2008). The establishment and active maintenance of these mental programs, commonly referred to as a ‘task set’ (Meiran, 2010; Monsell, 2003; Watt, 1905) or a ‘task model’ (Duncan et al., 2008), is likely to involve a limited capacity system. Duncan et al. (2008) have shown that an increase in the number of instructions for a given task can impair performance through ‘goal neglect’, the disregarding of a task requirement even though later tests show the task itself has been understood and remembered (Duncan, Emslie, Williams, Johnson, & Freer, 1996). Thus, although information regarding instructions can be stored in long-term memory, task sets must be held in an online system and compete for limited capacity resources. Duncan et al. (2008) also found that such goal neglect is more likely in participants who perform poorly on Cattell’s Culture Fair Intelligence test, a measure of fluid intelligence, and in patients with frontal lobe damage. Fluid intelligence and prefrontal cortex are both closely linked to working memory capacity (Kane & Engle, 2002), therefore suggesting that task set might depend on a limited capacity working memory.

While the goal neglect paradigm presents strong evidence for the importance of executive processing in initially performing a new task, once the set has been established, performance appears to be no longer so heavily dependent on level of intelligence or frontal lobe capacity. This limits informative evidence to the initial stages of the task and hence places constraints on the potential use of this paradigm for further exploring the nature and operation of task set. This is not a problem with the second and most extensively explored aspect of task set namely the capacity to switch from one well-learned task to another where performance is typically based on multiple switches (for reviews see Kiesel et al., 2010; Meiran, 2010; Monsell, 2003). The basic finding is a robust switch cost in both reaction time (RT) and error rate, which is higher in trials on which one task must be abandoned and another initiated. There is furthermore an extra cost when the two switched tasks contain similar features such as the same stimulus associated with a different response (Rogers & Monsell, 1995). This may be explained in terms of binding mechanisms whereby existing associations between stimuli and responses must be unbound and replaced by a different binding.

Our own focus is on a third aspect of task set, namely that of maintaining the set for later operation while performing other potentially disruptive activities. In everyday life, this tends to be referred to as multitasking and operates in many situations ranging from cooking breakfast to running a company. As in the case of goal neglect, it is heavily dependent on executive processing and very sensitive to frontal lobe damage (Burgess, 2000; Burgess, Veitch, de Lacy Costello & Shallice, 2000).

Our aim is to develop a relatively simple form of multitasking, which will allow the further investigation of the processes underlying the maintenance of a goal over a period during which an alternative and potentially similar operation is performed. For this purpose we adapted a paradigm developed by Wenke, Gaschler and Nattkemper (2007) in which an initial task is set up followed by an embedded second task that must be performed before the first task is completed. Wenke et al. (2007) were primarily interested in the effect of the ongoing load imposed by the initial task on the embedded task. They showed that mutual interference occurs between the two tasks with the disruption of the embedded task being greater when there is conflict between its constituents and those involved in the initial task (Wenke et al., 2007). In the task switching literature, embedded task paradigms are commonly used to investigate the mechanisms underlying action planning, and are typically concerned with the impact of the primary task action plan on the planning and performance of the embedded task (see e.g., Stoet & Hommel, 1999). However, we use this paradigm as a model for multitasking, being concerned with the performance of the initial task as a function of the intervening embedded task. We are interested in the nature of the temporary storage system whereby the initial task is maintained and protected from disruption by the embedded task. Like Wenke et al. (2007) we manipulate the relationship between the two tasks in order to identify possible mechanisms underlying any observed cross talk whereby one task influences the other. We approach our objective using the concurrent task paradigm whereby we selectively interfere with subcomponents of working memory looking for effects on cross talk between the two task sets.

We frame our study within the Baddeley and Hitch (1974) multicomponent working memory model. This is a theoretical framework that emphasizes breadth rather than detailed theoretical analysis, typically using a limited range of techniques in order to explore the interaction between attention and memory. In the 40 years since its initial proposal, it has proved robust and fruitful in casting light upon a range of cognitive activities in both healthy and clinical populations. In exploring a new area the method is typically to ask broad exploratory questions using simple methods. We regard this approach as complementary to approaches that attempt to focus a much more precise understanding within a tightly constrained framework. It is important to make this point, since we utilize a method developed by a group concerned with this more focused and precise analysis.

We do so because it provides a convenient task for our purpose, which is to study the maintenance of a single task during the performance of a complex alternative and potentially distracting embedded task. We do report the characteristics of the complex embedded task, but it is not the principal focus of our study, which aims to investigate the role of two different components of the multicomponent working memory model in maintaining the principal task against potentially disruptive ongoing activity. The multicomponent model assumes four separable but interacting subsystems (Baddeley, 2000; Baddeley, 2012). The first of these comprising an attentional control system, the central executive, together with two subsystems responsible for temporary storage of verbal and visuospatial information, namely, the phonological loop and the visuospatial sketchpad, respectively. A fourth component, a multimodal episodic buffer, responsible for dealing with novel bindings, was proposed by Baddeley (2000). Although we use the multicomponent model, it is important to note that our results are potentially compatible with other theoretical approaches, provided they distinguish between disruption of subvocal rehearsal, an attentionally relatively undemanding activity, and the greater executive demand imposed by a task such as backward counting. Evidence for this assumption is plentiful extending back to the work of Peterson and Peterson (1959) and the later demonstration that unlike backward counting, articulatory suppression does not result in the forgetting of short sequences such as consonant trigrams (Baddeley, Lewis & Vallar, 1984).

We therefore began by studying the effect of articulatory suppression on our complex task of maintaining two simultaneous sets, going on to investigate the potentially more demanding effect of increasing concurrent attentional load. First, we briefly review research studying the effects of these concurrent tasks on task switching.

One attempt to study the role of working memory in task switching found a major contribution from the use of subvocal rehearsal, reflected in a substantial slowing of performance when such rehearsal was prevented by articulatory suppression. Somewhat surprisingly, adding a further executive load led to only relatively small additional slowing (Baddeley, Chincotta & Adlam, 2001; Emerson & Myaki, 2003; Saeki & Saito, 2009). Given that the tasks concerned involved a simple requirement to switch on alternate trials, it seems likely that the relevant set served principally as a place holder in the sequence of responses which could easily be held in the phonological loop.

More long-term use of subvocal rehearsal was demonstrated by Saeki, Baddeley, Hitch and Saito (2013), who found that articulatory suppression continued to disrupt task switching across multiple post switch trials. However, although their paradigm involved maintaining a switching set over an extended delay, it is not like a typical multitasking situation in which several complex action plans may need to be held simultaneously. The embedded task paradigm has the potential to simulate multitasking by requiring a principal task set to be maintained while performing an embedded task. The principal task set is novel, the embedded task set is fixed, and the relationship between the two is varied in such a way as to provide information about any mutual interference between them.

We describe here two studies using the multicomponent working memory framework to investigate the role, if any, of the phonological loop and the central executive in setting up and maintaining a novel task set. The embedded task methodology we adapted from Wenke et al. (2007) is the ABBA paradigm illustrated in Figure 1. The principal task (A) was a choice reaction time task for which the instructions were simple rules mapping two letters onto two response keys, e.g.: If F – press left key, if C – press right key. These letter-key pairings changed unpredictably from trial to trial and the imperative stimulus requiring the left or right key press (‘C’ or ‘F’) appeared only after the embedded Task B was performed. The embedded task (B) was a font size judgment task in which two letters were presented side by side in the middle of the screen and participants had to identify which was the larger. Unlike the principal task, the instruction for the embedded task remained the same throughout the experiment.

Insert Figure 1 around here

Following Wenke et al. (2007), the compatibility of the stimulus-response pairings for the two tasks was varied to provide information about participants’ ability to segregate the two task sets. Thus in half the trials the letter pairs in the instructions for Task A (e.g., F and C) matched those in Task B, while in the other half they involved neutral non-instructed letter pairs (e.g., N and X). Trials with overlapping letter pairs could be either compatible or incompatible. Compatible trials were those in which the target (i.e., larger) letter in Task B appeared on the same side as that assigned to it by the instructions for Task A (See Fig. 1, left panel). Incompatible trials were those in which the target letter in Task B was presented on the opposite side to its instruction in Task A (See Fig. 1, right panel).

Wenke et al. (2007) found that performance was poorer on both Task A and Task B on incompatible than compatible trials, indicating interference between the stimulus – response bindings of both task sets. In subsequent work Wenke et al. (2009) found conditions under which performance was poorer on trials where the two tasks involved overlapping stimuli, with no effect of compatibility. They suggested that this pattern reflects strategy of deferring stimulus-response bindings for Task A until its imperative stimulus and that this results in a problem of segregating stimulus information for the two tasks. Here we use the term cross-talk to refer to interactions between simultaneously active task sets, noting that in general they can involve facilitation as well as interference (Dutta, Schweickert, Choi, & Proctor, 1995). Like Dutta et al. (1995), we regard cross-talk as an indicator of problems of segregation in keeping task sets separate. Following Wenke et al (2007, 2009) we regard compatibility and stimulus overlap effects as clues to the nature of such problems.

In the present experiments we explored which components of working memory underpin the capacity for segregation when a novel task set has to be maintained during the execution of an independent task set. Experiment 1 focused on the involvement of the phonological loop while Experiment 2 explored the involvement of the central executive.

# Experiment 1

Our first experiment used the ABBA paradigm to explore whether the phonological loop is involved in maintaining a novel task set in a multitasking condition. This seemed plausible given evidence that interfering with the phonological loop by requiring concurrent articulatory suppression disrupts task switching (Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003; Saeki & Saito, 2004; 2009). Participants performed the ABBA paradigm either on its own or while performing articulatory suppression, using the standard procedure of repeating a nonsense syllable. Wenke, Gaschler, Nattkemper and Frensch (2009) had suggested that participants may strategically choose to form the novel binding for Task A either immediately after listening to the instructions (i.e. before interpolated Task B) or only when encountering its imperative stimulus (i.e. after completing Task B). As we were not concerned to decide between these two possibilities, we required articulatory suppression throughout each trial of the ABBA task.

If either the primary or the embedded task requires access to the phonological loop for its execution, this would be indicated by a main effect of articulatory suppression on its performance. However, our main concern was to compare the effect of suppression on the amount of cross-talk between Task A and Task B. In the absence of concurrent articulation we expected to replicate Wenke et al’s. (2007) evidence for cross-talk, such that RTs and error rates on Tasks A and B were higher for incompatible trials than for neutral and compatible trials. Our key prediction was that if the phonological loop is involved in maintaining the segregation of the two task sets the amount of cross-talk should increase under articulatory suppression.

# Method

## Participants

Forty young adults (mean age=21 years) received an honorarium of £4 or course credit for participation. All reported having normal or corrected to normal vision and gave informed consent.

## Design

Articulatory suppression was manipulated between subjects with trial type (neutral, compatible and incompatible) varied within subjects. Participants were randomly assigned to two equal groups, one the articulatory suppression and the second a control group. The suppression group was required to perform articulatory suppression throughout the experiment, while no concurrent task was required of the control group.

## Implementation of the ABBA paradigm

Responses for the principal and embedded tasks were made using a button box containing 4 rectangular buttons arranged around a central round button as illustrated in Figure 1 (Cedrus Response Pad RB540). The left and right buttons were colored white and used for responses to the principal task (A). The up and down buttons were colored red and blue, respectively (or blue and red for half of the participants), and were used for responses to the embedded task (B). The central button was used to control events, as described below.

The principal task (A) was a binary choice reaction task with instructions mapping two letters onto two press responses, for example “If F, press left key, if C press right”. The letters appearing in the instruction changed on each trial. Importantly, the imperative stimulus (e.g., F or C) was only presented after completion of the embedded task (B).

Task B was also a binary choice reaction task but with separate response keys. It involved a font size judgment requiring an up or down key press response depending on the location of the larger of two letters that differed in font size (5 mm and 12 mm), displayed side by side in a grid. Half the participants were instructed to press red if the larger letter was on the right and blue if it was on the left. For the other half, the red and blue keys were assigned the other way round. Instructions for Task B were given at the beginning of the experiment and remained unchanged throughout.

The sequence of events on each trial was as follows. First, Task A instructions were displayed for up to 8 seconds. Participants could terminate this display by pressing the central round response button. This was followed by a 300 ms blank interval, a 300ms blank horizontal grid, and finally the two letters for Task B. The letters remained in view until the participant responded by pressing the red or blue button. After a 300 ms blank screen, the imperative stimulus for the principal task (A) was shown until the participant responded by pressing the left or right button. The response deadline for both tasks was set to 5 seconds and error feedback was given for both tasks by sounding a 200 Hz tone.

In order to check that participants were memorizing instructions for the principal task, catch trials were introduced in which an imperative letter was presented that had not appeared in the instructions for that trial. On catch trials participants were required to refrain from responding and wait for 5 seconds, until the next trial started. If participants responded on a catch trial, an error message appeared in red saying “responded although letter was not in the target set”.

The overlap between the principal and embedded tasks was manipulated as follows. On half of the trials, letter pairs presented in the principal task were also presented in the embedded task (target overlapping trials; see Fig. 1, left and right panel). Target overlapping trials were evenly divided into compatible and incompatible trials. Compatible trials were those in which the target letter in the embedded task appeared in the same location as the instructed response for the principal task (see Fig. 1, left panel). On incompatible trials, the target letter in the embedded task appeared in the opposite location (see Fig. 1, right panel). Trials with non-overlapping letters (see Fig. 1, central panel) served as a neutral baseline condition.

## Stimulus material and counterbalancing

In order to construct letter pairs for both tasks, letters of the alphabet were randomly assigned to two lists of 13. Permutations of letter pairs from one list were used for the principal task and for overlapping trials for the embedded task, which were divided evenly between compatible and incompatible trials. Permutations of letter pairs from the other list of 13 letters were used for the embedded task on neutral trials. Assignment of the two sets of letters to each task was counterbalanced across participants.

Across each set of 16 trials (8 neutral, 4 compatible and 4 incompatible), stimuli and responses were counterbalanced with equal numbers of stimulus types and key responses for each task. Each test block contained 80 trials, of which, 64 were regular trials (i.e. 4 replications of each of the 16 types just described), and 16 were catch trials. Catch trials were assigned to the same overlapping and response requirement as the critical manipulations.

A total of four blocks of 80 trials were presented to each participant, with a rest interval between each. Letter pairs for all conditions changed at each trial but could repeat between blocks. Furthermore, in half of the blocks, instructions for the principal task were presented with the ‘left key’ command in the upper part of the display and the ‘right key’ command in the bottom (as shown in Fig.1). In the other half of the blocks, this arrangement was reversed. This was done to guarantee that participants were reading the instructions and not just associating the upper letter to the left side and the bottom letter to the right side. Participants were told in advance that the arrangement would vary between blocks and that the order of blocks was random.

## Practice trials

Practice trials used digits as stimuli instead of letters. Digits from 0 to 9 were randomly assigned to two different lists and trials were constructed as in the experimental task. One block of 40 practice trials was given, comprising 32 regular trials and 8 catch trials.

## Procedure

The experiment was run using E-prime. Viewing distance from the computer screen was approximately 50 cm. Written and oral instructions were given on general task requirements with warnings about the occurrence of catch trials and the need for both speed and accuracy on both tasks.

General instructions were the same for both groups. The first two practice trials were experimenter-paced to illustrate the task. Participants in the control group worked through the rest of the practice trials by themselves; those from the suppression group received new instructions about the secondary task after 20 practice trials. The suppression group was required to say ‘da da da’ at a moderate and constant pace of approximately two utterances per second. A few minutes were allowed for practicing uttering the sounds at the appropriate rate. Finally, the last 20 practice trials were performed with concurrent articulation.

After completion of practice trials involving digits, written instructions were repeated for the experimental task using letter stimuli. Participants in the suppression group were required to perform the secondary task continuously throughout each block with rests between blocks.

# Results

One participant produced response times more than 3 standard deviations from the group mean and was excluded from data analyses, reducing the suppression group to 19 participants. Catch trials produced low error rates for both groups, mean (SD) percentage errors being 1.0 (1.4) for the control group and 1.8 (3.8) for the suppression group. Mean reaction times (RTs) were determined for regular trials with correct responses on both tasks, resulting in the exclusion of 9.4% and 10.6% of trials for the control and suppression groups, respectively. RTs that deviated more than three standard deviations from an individual’s mean were discarded, comprising 3.4% and 3.2% of trials for the control and suppression groups, respectively.

## Principal task

Figure 2 summarizes RTs and error rate data for the principal task. RTs were entered into a mixed ANOVA combining group (control, suppression) and trial type (neutral, compatible and incompatible). The effect of group was not significant, F (1,37) = 0.25, p = .87, η2 = .001, indicating that suppression did not impair overall performance. There was however a significant effect of trial type, F (2,74) = 35.3, p < .001, η2 = .48. This reflected slower responding on incompatible trials than either neutral, p < .001, d = .38, or compatible trials, p < .001, d = .34, which did not differ, p = .56, d = .03. Finally there was no interaction between group and trial type, F (2,74) = 0.27, p = .76, η2 = .007. In short, performance of the principal task was affected by the nature of the embedded task, but was not influenced by concurrent articulatory suppression.

Insert Figure 2 around here

Error analyses showed a similar pattern with no effect of articulatory suppression, F (1,37) = .18, p = .67, η2 = .005, and no interaction between group and trial type, F (2,74) = 0.75, p = .47, η2 = .02. The effect of trial type was however slightly different from that on RTs, with compatible trials having a lower error rate than either neutral, p < .001, d = .59, or incompatible trials, p < .001, d = .07, and no difference between incompatible and neutral trials, p = .09, d = .23.

In summary, when speed and accuracy are considered together, performance of the principal task showed cross-talk in the form of a compatibility effect, being poorer in the incompatible condition than the compatible condition, with the neutral condition somewhere in between. However, there were no effects of concurrent articulation.

## Embedded task

The results are shown in Figure 2 and were analyzed by ANOVA which again showed no significant effect of current articulation, F (1,37) = 0.1, p = .92, η2 < .001, nor any interaction between this and compatibility, F (2,74) = .55, p = .58, η2 = .015. There was an overall effect of compatibility, F (2,74) = 30.6, p < .001, η2 = .45, with neutral trials being faster than compatible trials, p < .001, d = .26, which in turn were faster than incompatible trials, p < .01, d = .14. Error rates were uniformly low and were not further analysed.

In summary, the embedded task showed cross-talk in the form of effects of stimulus overlap and task set compatibility, in that neutral trials were fastest and incompatible trials were slower than compatible trials. As for the primary task, however, were no effects of concurrent articulation.

# Discussion

Experiment 1 had two main objectives, first to establish that the embedded task did influence performance on the primary task in a predictable way, as previously reported by Wenke et al. (2007), and secondly to test the hypothesis that maintaining the segregation between the two task sets would be disrupted by articulatory suppression. In the case of the primary task, we broadly replicated Wenke et al. (2007), despite our use of less extensive practice and a session lasting one hour rather than two. Thus, participants performed at an acceptable accuracy level across conditions and showed the expected drop in performance on the primary task when the embedded task involved incompatible as compared with compatible responses to the same letter stimuli, with neutral trials in between. Performance on the embedded task was also broadly consistent with Wenke et al. (2007) in showing poorer performance on overlapping compared with neutral trials. Once again incompatible trials produced the poorest performance, but, interestingly, compatible trials also impaired performance relative to neutral trials, indicating an additional problem of coping with stimulus overlap.

Our main question concerned the influence on the cross-talk between the two tasks of articulatory suppression, a variable that has proved to have robust interfering effects in a range of task switching paradigms (Baddeley et al., 2001; Emerson & Miyake, 2003; Liefooghe, Vandierendonck, Muyllaert, Verbruggen & Vanneste, 2005; Saeki & Saito, 2004; 2009; Saeki et al., 2013). However, we found no suggestion of an impairment suggesting that forming, maintaining and implementing a novel task set does not, in this case at least, rely on subvocal rehearsal. There are of course many differences between the present and earlier studies, which were typically based on rapidly alternating fixed task sets, for example to successively add and subtract a digit from a sequence of single numbers. While our task takes longer, simple elapsed time does not seem to be the crucial difference, given the observation by Saeki et al. (2013) of an effect of articulatory suppression on switching after delays involving 24 intervening trials. One potentially important factor is that the present primary and embedded tasks contained common letters that served different and sometimes incompatible functions, and these would be hard to keep apart by relying on subvocalisation. It is perhaps also important to note that in earlier studies of task switching, suppression typically slowed down responding but did not prevent accurate performance. It seems possible, therefore, that subvocal speech in these studies provided a simple way of keeping track with the arithmetic task by repetitively uttering “plus minus, plus minus”. The fact that although articulatory suppression slowed performance, it did not dramatically increase error rate suggests that such verbal assistance is not essential. In contrast, simple place marking would be insufficient to support performance in the present more complex situation of maintaining the segregation of potentially overlapping task sets. Indeed, viewed as a system specialised for maintaining verbal sequences, the phonological loop would seem to lack the necessary computational properties for controlling cross-talk between simultaneously active task sets.

Our next question concerned the role of executive processes in maintaining task set segregation. Previous evidence has shown that adding an executive load to articulatory suppression in a task switching paradigm led to only a relatively small further decrement (Baddeley et al., 2001). This could be interpreted in at least two ways, one being that executive processes do not play a major role in the maintenance and operation of task set, the other being that the task set in question, simple alternation, placed only a minimal load on executive resources. Experiment 2 investigates this possibility by adding an executive load in the embedded task paradigm where the need to maintain a variable task set while performing an interpolated task seems likely to load the underlying system more heavily. If executive processes do play an important role in maintaining a novel task set, then we would expect to detect a clear disruptive effect of requiring an attention-demanding concurrent task. More specifically, if executive processes are important in maintaining the segregation between simultaneously active task sets, we would also expect to see more cross talk between the primary and embedded tasks when performing a demanding concurrent task.

# Experiment 2

To investigate the importance of attentional control processes in implementing newly instructed actions in face of an interfering task, participants performed the embedded task ABBA paradigm while counting backwards from a three-digit number at the same time. An articulatory suppression condition served as a control for the speech-based component of the more demanding task of counting backwards, which is assumed to load the central executive component of working memory (Allen, Baddeley & Hitch, 2006; Baddeley et al., 2001).

# Method

## Participants

Sixty-one University of York undergraduates (mean age=21 years) received a small sum or course credit for participation. All reported having normal or corrected to normal vision and gave informed consent.

## Design

A within subjects design was used, in which all participants performed the ABBA paradigm with both types of concurrent task, articulatory suppression (repeating a three-digit number) and counting backwards (counting backwards by 1 from a three-digit number). There were eight blocks of trials, with half of the blocks assigned to each concurrent task. Block order presentation was random. As in Experiment 1 the embedded task comprised equal numbers of neutral and overlapping trials, with the latter equally divided between compatible and incompatible trials.

As one of the conditions involved the more demanding task of counting backwards, trial blocks were made smaller than in Experiment 1 so as to allow more frequent inter-block rests. Thus, each block contained 20 trials, of which 16 were regular trials and 4 were catch trials.

## Practice trials

Digits were used as the stimuli for practice trials, as in Experiment 1, in this case comprising three blocks with 20 trials each.

## Procedure

Before being introduced to the main task, participants practiced the concurrent tasks alone. A three-digit random number was presented in the middle of the computer screen and participants were asked either to repeat the number for two trials of 2 min each or to count backwards in decrements of 1, again for two 2 min trials (pilot study indicated that counting back in threes or twos resulted in unacceptably high error rates). Participants were asked to maintain repetition and counting at a constant moderate rate of approximately 2 numbers per second.

Overall instructions for the paradigm were provided next. The first four practice trials were experimenter-paced and were used to illustrate the task. Participants worked through the rest of the first practice block by themselves. For the next practice block, further instructions were given regarding concurrent articulatory suppression. A three-digit number was displayed in the middle of the screen at the start of the block and participants were required to repeat it continually until the end of the block. In the final practice block, participants were required to count backwards in ones from another three-digit number until the end of the block.

After completing the practice trials involving digits, general written instructions were repeated using letter stimuli. A three-digit number was presented at the beginning of each block with written instructions on whether to repeat it or count backwards. Each participant completed 8 blocks of 20 trials with a short rest interval between each. Each concurrent task was performed in four blocks, in random order.

# Results

Despite reducing the difficulty of the concurrent task to counting backwards in ones, 10 participants had error rates higher than 35% on catch trials suggesting they were either unable to memorize the instructions or were not properly engaged in the task. These participants were excluded from further analysis, leaving a sample of 51. Mean (SD) percentage of errors on catch trials for the included sample was 4.3 (7.1) under articulatory suppression and 11.0 (9.8) when counting backwards. A paired t-test showed there was a significant difference between conditions (t=-6.0; p<.001; d=-.78).

Mean RTs are shown in Figure 3 as a function of trial type (neutral, compatible or incompatible) and concurrent task (suppression or counting). Only trials with correct responses on both tasks were considered (excluding 21.8% trials). RTs that deviated more than three standard deviations from individual mean were discarded (3.4% of trials).

Insert Figure 3 around here

## Principal task

ANOVA conducted with RT data showed an overall effect of concurrent task, F (1,50) = 20.3, p<.001, ηp2 = .29, with counting backwards producing longer RTs than suppression, p<.001, d = .46. There was also a significant effect of trial type, F 2,100 = 15.8, p<.001, ηp2 = .24. Contrast analysis revealed that, for both concurrent task conditions, incompatible trials yielded significantly higher RTs than neutral, p<.001, d = .26, and compatible, p<.001; d = .27, trials, which did not differ from one another, p = .76; d = .02. There was no interaction between type of concurrent task and trial type, F (2,100) = .18, p = .83, ηp2 = .003.

For errors, ANOVA again showed a significant effect of concurrent task, F (1,50) = 45.5, p<.001, ηp2 = .48, with counting backwards producing more errors than suppression, p<.001, d = .84. There was also a main effect of type of trial, F 2,100 = 37.3, p<.001, ηp2 = .43, and an interaction between type of trial and concurrent task, F (2,100) = 8.2, p<.001, ηp2 = .14. Planned comparisons revealed a different pattern of errors in the counting and suppression conditions. With articulatory suppression, incompatible trials yielded more errors than either neutral, p<.01, d = .50, or compatible trials, p < .01, d = .52, which did not differ from one another, p =.43, d = .08. When counting backwards by one, incompatible trials also yielded more errors than either neutral, p<.01, d = .33, or compatible trials, p < .01, d = .33, however compatible trials yielded fewer errors than neutral trials, p<.001, d = .58. Comparisons between each trial type (neutral, compatible and incompatible) in each concurrent task revealed that the counting backwards condition produced more errors for all types of trials, with all p<.01.

In summary, RTs for the principal task were slower with counting backwards than with articulatory suppression and showed broadly similar compatibility effects. Error rates were also much higher with counting backwards than with articulatory suppression but showed a different pattern. Thus, while suppression led to a compatibility effect, backwards counting led to effects of both stimulus overlap and compatibility.

## Embedded task

ANOVA on RT data for the embedded task yielded significant effects of concurrent task, F (1, 50) = 34.32, p<.001, ηp2 = .45, with the counting condition slower than suppression, p < .001, d = .34. The main effect of trial type was also significant, F (2,100) = 10.87, p<.001, ηp2 = .18, as was the interaction between concurrent task and trial type, F (2,100) = 5.17, p<.01, ηp2 = .1. With articulatory suppression, incompatible trials produced slower RTs than either neutral, p<.001, d = .27, or compatible trials, p<.01, d = .21, which did not differ from one another, p = .37, d = .07. With concurrent counting, the pattern was different. In this case incompatible and compatible trials both yielded slower RTs than neutral trials (p<.001, d = .29 and p<.001, d = .33, respectively) but did not differ from each other, p = .49, d = .04. Comparisons between each trial type for each concurrent task revealed that the counting backwards condition yielded higher RTs for all trial types, all p<.05.

As shown in Figure 3 (lower right panel), error rates for the embedded task were too low to justify further analysis.

In summary, the embedded task was performed more slowly with concurrent counting than with articulatory suppression and RTs showed a different pattern. Thus, with backwards counting, there was a negative effect of stimulus overlap and no effect of compatibility. However, with articulatory suppression there was a compatibility effect and no discernible effect of stimulus overlap.

# Discussion

 Our main interest was in investigating the need for controlled attention in forming and maintaining a task set. For this purpose, we examined performance in the ABBA embedded task paradigm with two types of concurrent activity, articulatory suppression and backwards counting. As in Experiment 1, stimuli in the embedded task were either compatible, incompatible or neutral in relation to the principal task. The most striking feature of Experiment 2 was the dramatic effect of backward counting on performance of both tasks. Backward counting as typically used experimentally can vary in difficulty from counting in threes, the most common, to counting in twos or ones. Pilot studies suggested that threes or even twos proved too big a load for most participants, and even the lightest load of counting back in ones was too demanding for 10 participants to complete the study in a satisfactory way. This is in stark contrast to the effect of articulatory suppression, and to studies employing repeated task switching paradigms where suppression is virtually as disruptive as more executive verbal tasks (Baddeley et al., 2001; Emerson & Miyake, 2003; Saeki & Saito, 2004).

The main effect of concurrent counting backwards on both tasks indicates that limited capacity executive resources are necessary for multi-tasking when, as here, one of the task sets varies. Beyond this, changes in the pattern of cross-talk between the two tasks provides clues as to the role of executive resources. Under articulatory suppression, cross-talk consisted entirely of compatibility effects in both RTs and errors for both the principal and the embedded task. Thus, performance of both tasks suffered when the location of the imperative stimulus triggered an incompatible rather than a compatible stimulus-response binding. On the other hand, with backward counting only the principal task showed a compatibility effect, while stimulus overlap effects emerged for both tasks, in errors in the principal task and RTs in the embedded task. In summary, an executive load impaired performance of both tasks with increased evidence of mutual interference attributable to stimulus overlap.

 It is interesting to note here that performance under articulatory suppression was slightly different in the two experiments. Thus, in the suppression condition of Experiment 1, RTs in the embedded task showed effects of both compatibility and stimulus overlap, whereas in Experiment 2 they only showed an effect of compatibility. On the other hand, performance on the primary task under suppression was broadly similar in both experiments, showing effects of compatibility but not stimulus overlap. Although the difference is relatively small, it suggests that inclusion of the counting backwards condition may have affected the way participants approached the requirement to deal with the embedded task. We return to this point below.

# General Discussion

Our aim in this paper was to investigate the role of working memory in maintaining task set for a newly instructed action in the face of an interfering task. We used the ABBA paradigm developed by Wenke et al. (2007) where novel instructions for a principal task (A) are presented first followed by performance of an embedded task (B) with a fixed task set which in turn is followed by the imperative stimulus for the principal task and its execution. We chose this paradigm to impose a delay on maintenance of the set for task A, and because manipulating the overlap between stimuli in the two tasks has been shown to influence the amount of cross-talk between them, providing a potential window on how task sets interact (Wenke et al., 2007, 2009).

 Experiment 1 was clear-cut in showing no influence of articulatory suppression on either the principal or embedded task, suggesting that task set maintenance was not dependent on subvocal rehearsal. We did however find cross-talk between tasks, similar to that found by Wenke et al. (2007), consisting mainly of compatibility effects for both tasks, consistent with evidence that an instruction to perform an action is sufficient to create stimulus-response links similar to those obtained by extended practice (Brass, Wenke, Spengler, & Waszak, 2009; Cohen-Kdoshay & Meiran, 2007; De Houwer, Beckers, Vandorpe, & Custers, 2005). We also found that the amount and pattern of cross-talk was uninfluenced by articulatory suppression, again suggesting that participants did not use subvocal rehearsal to maintain the instructions for task A while task B was performed. This contrasts with simple repetitive task switching paradigms, where participants seem to rely on verbal self-instruction to keep track of which task they are performing (Baddeley et al., 2001; Emmerson & Myiake, 2003; Saeki & Saito 2009). However, the order of tasks in our own study was fixed, well practiced, with external cues for each task that were clear and explicit. Hence, there was no need for self-cuing which task to perform each time. Furthermore, as noted earlier, one of the main challenges posed by the embedded task paradigm is keeping the stimulus response bindings for the two task sets apart (Wenke et al., 2007) and in retrospect it is difficult to imagine how this might be achieved within the phonological loop, a subsystem specialized for storing sequences rather than dual control programs.

 In contrast to articulatory suppression, loading the central executive system has previously been shown to disrupt a wide range of cognitive tasks (Baddeley & Hitch, 1974; Baddeley et al., 2001, Rao & Baddeley, 2013; Peterson & Peterson, 1959) as was shown in Experiment 2, where counting backwards led to poorer performance of both the principal and embedded tasks when compared with articulatory suppression. Interestingly, counting backwards altered the pattern of cross-talk for both the principal and embedded tasks, which each showed interference due to a combination of stimulus overlap and stimulus-response compatibility effects. It seems therefore that resources for executive control are particularly important for dealing with stimulus overlap in the present example of multi-tasking. In previous research using the ABBA paradigm it has been argued that interference due to stimulus overlap in the absence of a compatibility effect reflects a strategy of deferring stimulus-response binding of the principal task-set until presentation of its imperative stimulus (Wenke et al., 2009). If so, it is possible that backwards counting may have increased the probability of adopting such a strategy, though not to the complete exclusion of trials in which novel bindings are formed on instruction. The potential importance of strategies arose earlier when noting the existence of minor differences in the pattern of interactions between the two tasks under articulatory suppression in Experiments 1 and 2.

Overall, the present results suggest that limited capacity executive resources are involved in keeping apart simultaneously active task sets, by segregating stimuli as well as stimulus-response bindings, providing converging evidence for the view that task sets are held in an online system and compete for limited capacity resources (Duncan et al., 2008). Thus even though the embedded task set can be considered to be well learned and stored in long-term memory, it appears to be held online. Our identification of this system with the central executive is consistent with other evidence that goal neglect is found in patients with frontal lobe damage and individuals with low fluid intelligence (Duncan et al., 2008).

The fact that a concurrent task could disrupt performance is perhaps unsurprising. What is surprising is the magnitude of the disruption. Whereas counting back in threes is the standard concurrent task for preventing rehearsal during the retention of consonant or word triplets (Peterson & Peterson, 1959; Baddeley et al., 1984), this proved devastating to the capacity to maintain two concurrent task sets while even counting back in ones proved too difficult for some participants.

We note here that the present approach is deliberately exploratory, designed to obtain an initial answer to the general question of the dependence of task set maintenance on executive resources, giving a positive answer. The nature of executive involvement is however likely to be extremely dependent on the characteristics of the relevant task sets. Hence, a more detailed investigation into how a novel task set is formed from verbal instructions and how it is maintained over a filled interval will eventually require further experiments, probably involving simpler concurrent tasks than the ones that we have used. Our more complex instructions have however allowed us to benefit from the earlier work of Wenke et al. (2007, 2009) in demonstrating the nature of the cross talk between tasks. Whether simpler tasks can be devised that are equally informative remains to be seen.

In conclusion, the issue of how we transform verbal commands into action is not typically regarded as a memory problem, being more usually studied in terms of perception and action. We explored these processes using an ABBA embedded task procedure that required two task sets (A varying and B fixed) to be active simultaneously, exploring the role of working memory through the effects of different concurrent tasks on behavior. Our main findings were that performing a demanding concurrent task impaired performance of both tasks and led to increased cross-talk between the two task sets, particularly when they involved the same stimuli. We interpreted these findings as showing that limited capacity executive resources are important for maintaining and implementing task sets, with one function being to control cross-talk between simultaneously active but logically independent task sets. This is consistent with the idea that both novel stimuli and their bindings to actions are maintained in a limited capacity temporary storage system, perhaps reflecting what Oberauer (2009) has termed implicit working memory. While this concept has not been discussed within the multicomponent working memory model (though see Baddeley, 2012), it could be regarded as referring to the range of processes including those necessary for strategy choice and rehearsal control that play an important role in the operation of working memory without themselves being necessarily accessible to conscious awareness. They are currently defined negatively by the absence of direct awareness, which implies lack of direct access to the episodic buffer and are likely to comprise a number of potentially separable processes. Our current results suggest however that one or more of these is highly dependent on a limited capacity executive control system of the type proposed by Duncan et al. (1996; 2008).

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# Figure Legends

Figure 1. Schematic illustration of the ABBA paradigm: a new instruction was presented at each trial, followed by a size judgment task; the imperative stimulus for the Principal task (A) was only presented after response for the Embedded task (B) had been given; position of the letters presented on Embedded task (B) could be compatible or incompatible to the stimulus response mappings given in Principal task (A).

Figure 2. Performance for control and articulatory suppression groups in Experiment 1, plotted in function of each condition: neutral, compatible and incompatible trials. Upper panels show RT and error rates for Principal task (A); lower panels show RT and error rates for Embedded task (B).

Figure 3. Performance under articulatory suppression and counting backwards concurrent tasks in Experiment 2, plotted in function of each condition: neutral, compatible and incompatible trials. Upper panels show RT and error rates for the Principal task (A); lower panels show RT and error rates for Embedded task (B).