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Temporal order in memory and interval timing: An interference analysis

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Abstract

The effect of varying load in memory tasks performed during a time interval production was examined. In a first experiment, increasing load in memory search for temporal order affected concurrent time production more strongly than varying load in a spatial memory task of equivalent difficulty. This result suggests that timing uses some specific resources also required in processing temporal order in memory, resources that would not be used in the spatial memory task. A second experiment showed however that although increasing load affected time intervals when the concurrent task was to search for temporal order, the same manipulation had a much smaller effect on produced intervals when the task was to maintain information on temporal order in memory. These results underscore the importance of considering the specific resources and processes involved when the interference between timing and concurrent nontemporal tasks is analyzed.

Keywords: Timing; Memory; Attention; Interference

PsycINFO Classification: **2340** Cognitive Processes

Temporal order in memory and interval timing: An interference analysis

1. Introduction

The interference effect is one of the most consistent findings in research on time perception (Brown, 1997). This effect generally refers to a disruption in perceived time when some nontemporal task is executed simultaneously and ~~,~~ more precisely to a shortening of perceived time relative to conditions in which timing is performed alone. Increasing difficulty of the nontemporal task typically leads to an increase of the interference effect. These results are classically observed in prospective timing tasks, when participants know in advance that temporal judgments are required. A shortening of perceived time with increasing difficulty of concurrent processing was obtained with a wide range of tasks involving perceptual (Brown, 1985; Casini & Macar, 1997; Coull, Vidal, Nazarian, & Macar, 2004; Field & Groeger, 2004; Macar, 2002; Zakay, 1993), memory (e.g., Fortin & Couture, 2002; Fortin & Massé, 1999; Hicks & Brundige, 1974; Rammsayer & Ulrich, 2005), and verbal (McClain, 1983; Miller, Hicks, & Willette, 1978; Zakay, 1989) processing.

A common interpretation of these results is that temporal processing, defined as accumulating temporal cues in a timer mechanism, requires attention (Brown, 1985; Meck, 1984; Thomas & Weaver, 1975; Zakay, 1989). When attention must be shared with some concurrent task also requiring attention, the accumulation process is disrupted. Over a certain period of time, missing cues will lead to a general decrease in the number of accumulated temporal cues, hence shorter perceived duration. This attentional allocation model accounts for numerous results in time estimation research, where underestimation is directly related to the level of difficulty of concurrent nontemporal tasks (Fortin & Massé, 1999; Sawyer, Meyer, & Hauser, 1994; Zakay, Nitzan &

Glickson, 1983) or to the proportion of attention deliberately allocated to nontemporal features of a stimulus (Casini & Macar, 1997; Coull, Vidal, Nazarian, & Macar, 2004).

This attentional framework widely used to interpret behavioral data in timing research has been supported recently by a review of brain imaging data showing that patterns of activation observed in a variety of timing tasks include areas such as the dorsolateral prefrontal, the anterior cingulate cortex and/or the right parietal cortex, all areas involved in attentional systems and working memory (Macar, Lejeune, Bonnet, Ferrara, Pouthas, Vidal & Maquet, 2002). The involvement of these areas would derive from relationships between attention and the temporal accumulator as assumed in most current timing models. The accumulator is assumed to be located in striatal structures, a hypothesis based on brain lesions and pharmacological manipulations in animal studies (see Gibbon, Malapani, Dale, & Gallistel, 1997; Meck, 1996 for reviews) which have revealed the role of the striato-frontal dopaminergic system in time processing. Such findings are in accordance with neuropsychological data showing that lesions in the basal ganglia (Harrington & Halland, 1999; Rammsayer & Classen, 1997) may lead to deficits in time discrimination, as do lesions in the cerebellum (Ivry & Keele, 1989; Malapani, Khati, Dubois & Gibbon, 1997). Support for the involvement of the striato-frontal dopaminergic system in timing is finally found in brain imaging studies showing clear activation of the supplementary motor area (SMA), which is part of the striatofrontal pathway (Jürgens, 1984), during timing tasks (e.g., Coull, Vidal, Nazarian, & Macar, 2004).

Despite the numerous studies supporting the idea of a strong relationship between attention and timing, some behavioral data from the timing literature can obviously not be explained by a simple attentional allocation model. For example, in a systematic analysis of bidirectional interference between temporal and nontemporal tasks, Brown (1997) noted that ~~-~~ when three nontemporal tasks, pursuit rotor tracking, visual search and mental arithmetic, were performed with ~~producing~~ 2- or 5-s interval productions, temporal production was disrupted by the three tasks whereas only mental arithmetic was disrupted by timing. According to Brown, a more sophisticated framework than a general attention allocation model, such as the multiple resource ~~-~~model (Wickens, 1984, 1991, 1992) or the working memory model (Baddeley, 1986, 2000; Baddeley & Hitch, 1974) is needed to account for this pattern of results.

Similar effects with mental arithmetic were obtained in a recent study, in which cognitive tasks were carried out with time discrimination of short (100 ms) and long (1000 ms) intervals in a dual-task paradigm (Rammsayer & Ulrich, 2005). In one experiment, mental arithmetic (addition of digits) was performed concurrently with time discrimination (Experiment 1). In two other experiments participants had to recognize letters (Experiment 2) or a visual pattern (Experiment 3) after the time discrimination task was completed so that letter and visuospatial patterns had to be retained in memory while the temporal task was executed. Whereas adding digits during time discrimination disturbed timing performance, letter or visual pattern recognition did not. As stated by the authors, the absence of interference from retention tasks in Experiments 2 and 3 may be explained by the fact that these tasks involved passive storage of information essentially, which was shown in previous studies not to affect concurrent timing (Fortin & Massé, 1999; see also Field & Groeger, 2004); ~~, and possibly also of a~~the relatively low level of task difficulty in those experiments may also have been a factor. There was a slight effect of ~~performing~~ concurrent timing ~~concurrently~~ on recognition errors in the spatial memory task, but disruption of recognition in the visuospatial task was clearly weaker than the corresponding effect of arithmetic on timing. In addition to supporting attentional models of time estimation, Rammsayer & Ulrich's study suggests that time discrimination ~~seemed~~ is especially affected by active processing in working memory when ~~involving~~ functions associated with the central executive are involved. This finding is in agreement with results from Brown's study and importantly, it was found with discrimination of both short and long intervals.

In the multiple resource model, ~~A~~attentional resources are assumed to be distributed in multiple pools defined in terms of processing stages (perceptual/central resources vs. response resources) and processing codes (spatial vs. verbal resources) (Wickens, 1991). In Brown's (1997) analysis, assuming that mental arithmetic and timing are both associated with perceptual/central resources (and possibly verbal resources if the timing task permits subvocal counting)~~,~~ leads to the prediction of clear bidirectional interference between the two tasks. ~~should be observed.~~ Visual search would involve primarily perceptual/central and spatial resources, which would explain why ~~finding~~ only unidirectional interference with timing is reported with ~~from these~~ this type of task~~s~~. Although pursuit rotor tracking (?) would require spatial and response-based resources essentially, ~~some~~ central resources used to coordinate concurrent execution of this task with time production could ~~explain~~ account for ~~that some~~ the effects ~~was~~ observed on timing.

Similarly, a working memory model composed of a central executive, a phonological loop and a visuospatial sketchpad (Baddeley, 1986; Baddeley & Hitch, 1974) would explain the interference between mental arithmetic and timing by some contribution of the central executive in both tasks (possibly by an executive timing subsystem), and perhaps of the phonological loop also. Visual search and pursuit rotor tracking would rely mainly on the visuospatial sketchpad, reducing competition for central timing resources. This interpretation assumes that timing is controlled mainly by the central executive, which is also responsible for coordinating and scheduling processes in dual-task situations (Brown, 1997). In this view, timing would rely to a much lesser extent on the phonological and visuospatial subsystems, their ~~and the~~ involvement being mainly limited ~~of these ones would be particularly related~~ to the use of strategies such as counting.

A previous experiment showed that ~~the~~ interference ~~on~~ with concurrent timing was increased if~~,~~ -- in addition to deciding whether a memory item was present or not -- ~~,~~ the difficulty of item recognition was increased by asking participants to verify the temporal position of the probe (Fortin & Massé, 1999, Exp~~.~~ 1).~~-~~ This result could be explained by the increased difficulty of the memory task when temporal order must be processed which would lead to ~~, hence~~ increased demands ~~of~~ on general undifferentiated resources. Alternatively, this result could be explained by specific resources being required simultaneously in processing temporal order in memory and timing. This issue was examined in the first experiment of the present study~~,~~ by comparing the effects of either temporal or spatial memory-based processing ~~temporal position and of processing spatial position in memory~~ on concurrent time production. ~~-~~Two memory tasks of comparable levels of difficulty should interact similarly with concurrent timing if the need for general resources was the main factor explaining the effect of processing temporal information in Fortin & Massé's study. In contrast, if their result was due to specific common resources required by temporal memory processing and time production, the effect of increasing load in a temporal order memory task should be stronger than the effect of increasing load in a spatial memory task. This might be expected given that, as summarized in Brown's (1997) analysis, sequential order information is considered as one of the main attributes of psychological time (e.g., Fraisse, 1984); ~~and that~~ to the extent that temporal order is related to perceived duration, it may be assumed that they both involve similar processing resources.

Whereas processing temporal information interfered with temporal production in Fortin & Massé's (1999) study, produced intervals were not affected by increasing the number of items to be maintained in memory in their temporal order of presentation. This dissociation between the effects of processing and maintenance of information ~~in memory~~ on concurrent time production was investigated thoroughly in a subsequent study; results showed ~~, in which there was no effect of~~ that increasing the number of colors or tone timbres to retain during a time production task had no effect (Field & Groeger, 2004, Experiments 2 and 3) whereas retention of pitch information or tone durations showed load-related effects (Experiments 1 and 4). The interference from pitch maintenance was considered as a particular case, but interference from maintenance of tones durations was attributed to the common requirement of retaining temporal information in the memory task and in the time production task. In the second experiment of the present study, the number of items to be maintained in their correct temporal order was varied during a time interval production task~~,~~ and this condition was compared directly with a similar load manipulation involving the retrieval of ~~retrieving~~ information on temporal order. Although previous results (Field & Groeger, 2004; Fortin & Massé, 1999; Rammsayer & Ulrich, 2005) suggest that a dissociation should be obtained such that produced intervals would lengthen with increasing load in the processing task but not in the retention task, increasing load in the passive retention condition might also affect time production because the memory and timing tasks both require ~~to~~ the maintenance of ~~maintain~~ temporal information.

In Experiment 1, we examined whether increasing load in a temporal memory task and in a spatial memory task would affect concurrent time production similarly. In Experiment 2, we compared the relative effects of increasing load either in processing ~~and~~ or in maintaining ~~maintenance of~~ temporal order information on time production. In the two experiments, letters were memorized. A probe was then presented and a decision was made on its temporal (Experiments 1 and 2) or spatial (Experiment 1) position in the memory set. This decision was made either during a time interval production (Experiments 1 and 2) or immediately after its termination (Experiment 2). In both experiments, the main question of interest was whether increasing load, defined as the number of letters in the memory set, would have different effects in the experimental conditions that were compared (spatial vs. temporal in Experiment 1, and processing vs. maintenance in Experiment 2).

2. Experiment 1

A memory task in which participants verified the temporal position of a stimulus in a memorized sequence of letters was contrasted with a task in which the spatial position of a stimulus in a memorized matrix of letters was verified. In both tasks, the number of memory items (set size) was varied (two or four). The relative difficulty of the tasks was first evaluated in a reaction time (RT) condition by testing whether increasing set size had a comparable effect with the two tasks. Then, in a concurrent processing (CP) condition, each task was performed concurrently with time production and the effect of increasing set size on produced intervals ~~with the two memory tasks~~ was examined.~~compared.~~

2.1 Method

2.1.1 Participants

Twenty-five participants, 15 women and 10 men, aged between 18 and 63 ~~years old~~ (mean age = 25.5; *SD*: 9.17) took part in the experiment. The participants, students or workers at Université Laval, received $10 for their participation in the RT condition, $20 in the CP condition. They were all naive regarding the experimental hypotheses.

2.1.2 Apparatus and stimuli

Stimulus and feedback presentations as well as data collection were controlled by a PC-compatible computer using the MEL (Micro Experimental Laboratory) software system. The visual stimuli were displayed on an IBM VGA color monitor with a 20 x 27 cm screen. Responses were provided by pressing one of three keys on the numerical keyboard of the computer. Reponses times were recorded to the nearest millisecond. The participants were tested individually in a sound-attenuated test chamber, where they were seated at an approximate distance of one meter from the screen.

The set of items used in the experiment was composed of seven consonants (D, Q, G, R, S, P, F) and three vowels (A, E, U). Memory-set size (*n* = two or four different letters) randomly varied from trial to trial with the constraint that each set size appeared equally often across the experiment (?). ~~, t~~The letters constituting the memory set, and the probe letter (*n* = 1) were selected randomly and varied from trial to trial. A letter was never repeated in a memory set. [was each temporal or spatial position tested equally often?] The letters were presented in white on a black background and subtended a visual angle of 0.2º in height and 0.4º in width.

2.1.3 Procedure

Fifteen participants were randomly assigned to the RT condition. Each of these fifteen participants was tested both with the spatial and temporal memory tasks in four experimental sessions, that is, two successive sessions with the spatial task and two successive sessions with the temporal task. Participants were tested with the spatial and the temporal tasks in counter-balanced order. [were all these sessions completed within one visit?]

Ten other participants were tested in the CP condition, which included two sessions in which participants practiced producing a 2.7-s target interval. Practice sessions were followed by four experimental sessions divided in two successive experimental sessions with the spatial task and two successive sessions with the temporal task. Participants were tested with the spatial and temporal tasks in counter-balanced order. [were all these sessions completed in one sitting or did participants complete these sessions on different occasions?]

2.1.3.1 RT condition

Each of the four sessions included five blocks of 36 trials, one block of practice trials and four blocks of experimental trials. There were 30-s rests between blocks. Sessions lasted between 20 and 30 min. An experimental trial began with the presentation of the word “Ready” in the middle of the screen. The word “Ready” remained present until participants initiated the trial by pressing the “2” key on the numerical keyboard. This keypress triggered the letter presentation as described below.

Schematic illustrations of experimental trials in the spatial and temporal tasks are presented in Figures 1a and 1b, respectively. As illustrated in Figure 1a, the letters of the memory set appeared simultaneously in the spatial task. When four items were presented, they were placed on two rows in the four corners of an imaginary square. When the memory set comprised two letters, they appeared on a single row in a middle position between the top and bottom of the square. The letters remained present for one second per item, that is, for two and four seconds when two and four items were presented, respectively. After the memory-set presentation, an asterisk (*) appeared, serving as a fixation stimulus until the participant pressed the “2” key anew. A probe letter was presented 500 ms later at one of the spatial positions where letters had been memorized. The other locations were filled with a neutral stimulus, a number sign (#). The probe remained present until the response was provided. The instructions were to press the “1” key as quickly as possible when the spatial position of the probe was correct or the “3” key when the position was incorrect.

Insert Fig. 1 about here

In the temporal task, each item of the memory set was presented successively for 1 s at the same location on the screen, with no delay between items (see Figure 1b). After the memory set presentation, a fixation stimulus (*) appeared and remained present until the participant pressed the "2" key anew. This keypress triggered the simultaneous presentation of a probe letter and of a digit, the digit being placed just below the probe. The two stimuli, probe and digit, remained present until the participant responded to the temporal order task. The instructions for responding maintained the same mappings ~~were~~ as ~~in~~ the spatial task. Participants were to respond by pressing the "1" key if the digit corresponded to the temporal position of the item and they were to press the "3" key if the digit did not correspond to the temporal position of the item. As in the spatial condition, the probe item was always taken from the current-trial memory set.

In both memory tasks, ~~a~~ visual feedback (Correct or Error) was ~~presented~~ provided for 1 s immediately after the response. The feedback was followed by the word "Ready", which informed participants that they could initiate the next trial when ready. In both memory task conditions, participants were asked to fixate the center of the screen from the time they started the trial by pressing the "2" key until the end of feedback presentation. The probe was always present in the memory set and the position of the probe was selected randomly on each trial. The number of trials at each set size and the number of positive and negative response trials were balanced within blocks of trials. Response times and response accuracy were recorded. I would provide this information above – [where I inserted a question relating to the equal number of trials for each temporal or spatial position].

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2.1.3.2 CP condition

Participants completed six sessions in the CP condition, two practice sessions of temporal production followed by four experimental sessions in which the temporal or spatial memory task were executed concurrently with time production. Sessions lasted between 30 and 40 min. There was a 30-s break between blocks of trials within a session.

Practice sessions enabled participants to stabilize their time interval production performance. These sessions included four 48-trial blocks with feedback on produced intervals, and one 48-trial block without feedback. At the beginning of the experiment, participants were provided examples of the target interval to be produced with a 2.7-s tone. Participants were not informed of the interval duration in formal units of time. A trial started with a fixation stimulus (*) presentation. The task was to produce the target interval as precisely as possible by pressing the “2” key twice on the numerical keyboard. In the first four blocks, a visual feedback was provided, informing the participant that the temporal production was too short, correct, or too long, relative to a ~~within a~~ 10 % window centered on the 2.7-s interval standard. In the fifth block, no feedback was provided in order to practice participants producing without feedback.

The four experimental sessions included six blocks of trials. These sessions started with a 48-trial block of temporal productions alone with feedback as in practice sessions to reset the target duration. This first block was followed by a block of 12 practice trials introducing the CP condition, in which temporal production was performed with the memory task. Four 36-trial experimental blocks were then completed. In these blocks, a trial began with a fixation stimulus (*). When ready to begin the trial, the participant pressed the “2” key on the numerical keyboard. The following events varied according to the memory task to be performed as described hereafter.

The letters of the memory set were displayed simultaneously in the spatial task (see Figure 1c). Immediately after the memory-set presentation, a fixation stimulus (*) appeared and remained present until the participant pressed the “2” key to begin the temporal interval production. Seven hundred milliseconds later, a probe letter appeared at one of the possible spatial positions of the memory set items, with the remaining locations filled with a neutral stimulus (#). The probe was present until the participant ended the temporal production when she/he judged that the target interval had elapsed, by pressing the “1” or the “3” key depending on the correct or incorrect spatial position of the probe.

Each item of the memory set was presented successively for 1 s in the temporal memory task (see Figure 1d). A fixation stimulus (*) then appeared and lasted until the participant pressed the “2” key. Five hundred milliseconds after this keypress, the probe and digit were presented. They remained present until the target interval was terminated by pressing the “1” or the “3” key depending on the digit corresponding or not to the temporal position of the probe. A visual feedback on the response to the memory task was then presented for 1 s. No feedback was provided on time production in experimental trials. The feedback was followed by the word “Ready”, which indicated that the next trial could be started.

Note that in the CP condition, the probe was presented 700 milliseconds (ms) after the beginning of the temporal production when the interpolated task was the spatial memory task, whereas it was presented after 500 ms with the temporal memory task. It was decided to present the probe 200 ms later with the spatial task because, as described in the result section below, RTs in the spatial task were shorter ~~of about 200 ms~~ than in the temporal memory task by about 200 ms on average. The probe was therefore presented 200 ms later with the spatial task so that participants would not have more time to ~~time to~~ process the probe in the spatial than in the temporal task during the interval production, which might have favored a stronger interference effect with the temporal memory task.

2.2 Results and discussion

Data from the first experimental block (36 trials) had to be eliminated for one participant because he did not understand the task well. Trials in which an incorrect response was provided in the memory task were removed from the data set. These errors represented respectively 5.99% and 6.02% of the data in the spatial and temporal tasks in the RT condition, and 1.97% and 2.81% in the spatial and temporal tasks in the CP condition. Outliers ($\pm$ 3 *SD*s from the mean and *SD* of each participant) were then eliminated, which represented 1.45% and 1.38% of the data in the spatial and temporal tasks in the RT condition, 1.11% and 1.39% in the spatial and temporal tasks in the CP condition. For each participant, a mean RT or a mean temporal production was computed at the two values of set size in the spatial and temporal memory tasks [Given outliers and extreme responses can affect both RT and time production, I wondered if the same effects would be observed if median responses were examined rather than means]. In the RT and CP experimental conditions, two repeated measures ANOVAs were carried out with memory set size (two, four) and memory task (temporal, spatial) as factors, one on response times (RTs in the RT condition and temporal productions in the CP condition), and one on mean error rates.

2.2.1 RT condition

2.2.1.1 RTs

Table 1 shows mean RTs ~~in~~ for the memory tasks. RTs ~~were~~ significantly increased ~~significantly~~ with set size, $F(1, 14) = 35.91$, $p < .001$ and were significantly longer in the temporal than in the spatial task, $F(1, 14) = 29.52$, $p < .001$. The interaction between set size and memory task was not significant, $F < 1$. The absence of interaction reveals that the slopes of RT functions were comparable in the two memory conditions, 73 and 83 ms per item in the temporal and spatial tasks respectively, which means that increasing load had a similar effect on RTs in the two tasks.

2.2.1.2 Error rates

There was a slight increase in error rates with set size (see Table 1), an effect which happened to be marginally significant, $F(1, 14) = 4.40$, $p<0.055$. Neither the memory task nor the interaction between set size and memory task had significant effects on error rates, *Fs* < 1.

Insert Table 1 about here

The absence of interaction between set size and memory task shows that the rate of processing was equivalent in the spatial and temporal memory tasks, confirming that they were of equivalent levels of difficulty. Results in the RT condition also show that RTs were, on average, about 200 ms longer in the temporal than in the spatial task. This additional processing time may reflect the time necessary to encode the digit representing the temporal position in the temporal memory task and to translate the digit in information on temporal order. There was no such encoding and translation needed in the spatial memory task because there was a direct representation of the probe's position in the stimulus matrix. For this reason, in the CP condition, the probe stimulus was presented 200 ms later when the spatial task was interpolated in the temporal production than when the temporal memory task was interpolated (see Figures 1c and 1d).

2.2.2 CP condition

2.2.2.1 Temporal productions

Mean intervals produced with the spatial and temporal memory tasks are presented at the two values of memory-set size in Table 2. Produced intervals did not differ with the two tasks $F(1, 9) = 1.08$, $p = .33$. The absence of a significant difference in mean produced intervals with the spatial and temporal tasks shows that by presenting the probe 200 ms later in the spatial task than in the temporal task, we succeeded in our attempt to make concurrent processing time equivalent with the two tasks. The general effect of set size did not reach significance, $F(1, 9) = 2.86$, $p = .13$. The critical result however is that the interaction between set size and order condition was significant $F(1, 9) = 6.09$, $p = .04$. Tests of simple main effects showed that increasing set size lengthened produced intervals significantly when the temporal memory task was performed during the interval, $F(1, 9) = 5.58$, $p = .04$, but not when the spatial task was performed, $F(1, 9) = 1.16$, $p = .31$. Even though applying a correction for performing two tests of simple main effects would make the effect of set size marginally significant in the temporal memory task condition, the difference between effects of set size in the two memory conditions is significant, as revealed by the interaction.

Insert Table 2 about here

2.2.2.2 Error rates

Mean percent error rates in the memory tasks are presented in Table 2. Neither the effect of set size, $F(1, 9) = 1.29$, $p = .29$, nor the effect of memory task, $F(1, 9) = 1.48$, $p = .25$, nor the interaction between these two factors, $F(1, 9) = 2.04$, $p = .19$, were significant. These results show that accuracy in detecting the probe's position was equivalent in both tasks. This confirms that the

~~stronger~~ effect of set size when the temporal memory task was interpolated in produced intervals cannot be explained by some differential speed-accuracy trade-off favoring precision at the expense of speed of processing with the temporal task.

The main finding in Experiment 1 is that although the rate of processing was comparable in the spatial and temporal memory tasks as revealed by the results in the RT condition, the lengthening of produced intervals with increasing number of items was more important when the concurrent memory task involved searching for temporal order than searching for spatial position. This dissociation suggests that the need to process temporal information simultaneously in the temporal memory task and in the time production task contributes specifically to the interference effect in the CP condition. Searching for spatial order would use spatial resources not used in interval timing, which might reduce the competition for central timing resources.

This interpretation supports an analysis of interference between temporal and nontemporal tasks in terms of multiple attentional resources (Brown, 1997). Indeed, these data could not be accounted for within a simple attentional allocation model because according to this model, two tasks of comparable difficulty should have the same effect on concurrent time estimation. A better account is provided by a theoretical framework integrating specialized resources such as the working memory model (Baddeley & Hitch, 1974) or the multiple resource model (Wickens, 1984). As suggested by an analysis referring to specialized resources or subsystems, the interference between searching for temporal order and time production would be explained by the common use of the central executive and possibly of the phonological loop in working memory or, in a multiple resource model, by the concurrent use of central and possibly verbal resources. The non significant effect of increasing load in the spatial memory task on timing would be explained by spatial resources or the visual sketchpad contributing to performance in the memory task, but not in the time production task.

3. Experiment 2

Memory processing often perturbs concurrent timing but there is usually no such effect with maintenance of information in memory (Field & Groeger, 2004; Fortin & Breton, 1995; Fortin & Massé, 1999; Rammsayer & Ulrich, 2005). However, produced intervals were lengthened by increasing the number of tone durations to remember during an interval production, which was considered to be caused by both tasks requiring remembering temporal information (Field & Groeger, Exp. 4). In Experiment 2, we tested whether this reasoning might be extended to maintenance of temporal order with an experimental task very similar to that used in Experiment 1. In one condition, the memory probe was presented during the temporal interval production ("Probe-In" condition). This condition was compared to a condition in which the probe was presented after the temporal production was terminated ("Probe-After" condition). The memory set had therefore to be searched for temporal position during the interval in the Probe-In condition, whereas it had to be maintained in correct temporal order throughout the interval in the "Probe-After" condition. Although results from a previous experiment suggested that maintenance of temporal order in memory should not affect concurrent time production, the effect of processing and maintenance for temporal order in memory had never been compared directly and specifically as in the following experiment.

3.1 Method

The method used in Experiment 2 was similar to that used in Experiment 1 in ~~many~~ most respects. In the Probe-In condition, the task was almost identical to that in the temporal order condition of Experiment 1. The target interval to be produced was shorter, 2.0 s (vs. 2.7 s in Exp.

1) to enhance generality of results. The apparatus and testing conditions were the same as in Experiment 1, with the exceptions described below.

3.1.1 Participants

Seventeen participants, 8 men and 9 women, aged between 20 and 43 years old (mean age = 23.8; *SD* = 5.89) took part in the experiment. They received $20 for their participation.

3.1.2 Stimuli

The 20 consonants of the alphabet were used as stimuli. Memory-set size (*n* = two, four, or six different letters), memory items, and the probe letter (*n* = 1) were selected randomly and varied from trial to trial. [Same questions here – were there no constraints on this random selection? Was each position was tested an equal number of times? Where half the trials yes trials and half of them no trials?]

3.1.3 Procedure

Each participant was tested in two separate sessions completed in counter-balanced order in the two experimental conditions, Probe-In and Probe-After. Experimental sessions were preceded by three practice sessions, which included four 48-trial blocks with feedback on produced intervals followed by one 48-trial block without feedback. Trials were identical ~~as~~ to practice trials in Experiment 1, except that the target interval was 2.0 s. The two experimental sessions included five blocks of trials: a 48-trial block of temporal productions alone with feedback to reset the target duration, followed by four 36-trial blocks in which time production was executed either with processing or maintenance of temporal order in the concurrent memory task.

In the Probe-In condition, the probe and digit were presented 500 ms after the beginning of the temporal production as in Experiment 1. The temporal production was executed by pressing first the “2” key on the numerical keyboard, and then by pressing the “1” or “3” keys depending on the digit corresponding or not to the correct temporal position of the probe in the memory set. In the Probe-After condition, the beginning and the end of the temporal production were executed by pressing the “2” key. The key-press ending the interval production triggered the probe and digit presentation, and participants were instructed to press one of two keys, “1” or “3”, depending on the probe presenting a correct or incorrect position in the memory set. Trials were identical to those in the temporal order condition of Experiment 1 in all other respects.

3.2 Results and discussion

Trials with errors in the memory task were eliminated from the data set, which represented respectively 13.1% and 10.1% of the data in the Probe-In and Probe-After conditions, respectively. Outliers ($\pm$ 3 *SD*s from the mean and *SD* of each participant) were then eliminated, representing 1.46% and 0.3% of the data in the Probe-In and Probe-After conditions. Mean productions were computed at each set size for each participant, and repeated measures ANOVAs were carried out on mean produced intervals and on mean percent error rates in the memory tasks.

3.2.1 Temporal productions

Mean produced intervals in the Probe-In and the Probe-After conditions are presented at each value of set size in Table 3. The effects of memory set size, $F(2, 38) = 11.34$, $p < .001$, and of probe condition, $F(1, 19) = 12.82$, $p = .002$, were statistically significant but the interaction between these two factors was not significant, $F(2, 38) = 2.18$, $p = .13$. Given that the difference in slopes of production functions in the Probe-In and the Probe-After conditions was a major issue in this experiment, we conducted a trend analysis on these data. For the set size factor, this analysis showed a significant linear trend, $F(1, 19) = 13.78$, $p = .001$, and a non significant quadratic trend, $F < 1$. There was also a significant interaction between condition and set size for the linear trend, $F(1, 19) = 6.92$, $p = .016$, and no interaction for the quadratic trend, $F < 1$. The interaction for the linear trend revealed that the slopes in the Probe-In ($M = 53.93$) and the Probe-After ($M = 16.44$) conditions were different. Separate tests for trends in the Probe-In and the Probe-After conditions showed that the linear trend was significant in the Probe-In, $F(1, 19) = 16.44$, $p = .001$, but not in the Probe-After condition, $F(1, 19) = 2.59$, $p = .12$.

Insert Table 3 about here

3.2.2 Error rates

Error rates increased significantly with set size $F(2,38) = 63.91$, $p < .001$, and were higher in the Probe-In than in the Probe-After condition $F(1,19)$ $p = 12.54$, $p = .002$. The interaction between set size and probe condition was also significant $F(2,38) = 3.68$, $p = .04$. However, tests of simple main effects showed that the effect of set size was significant in the Probe-In, $F(2,38)$ $p = 68.28$, $p < .001$, as well as in the Probe-After condition $F(2,38)$ $p = 27.42$, $p < .001$.

Taken together with the analysis of temporal production data, these results show that the effect of increasing memory load was weaker in the Probe-After than in the Probe-In condition. Nevertheless, memory load affected accuracy when items had to be maintained during the temporal interval. This dissociation is in agreement [????] with previous results showing an absence of interference from maintenance of information in memory on concurrent timing with other memory tasks (Field & Groeger, 2004; Fortin & Breton, 1995; Fortin & Massé, 1999; Rammsayer & Ulrich, 2005) but shows that maintenance of temporal order may have some effect on timing.

4. General discussion

Varying load had comparable effects on reaction times with a temporal memory task and a spatial memory task in Experiment 1 of the present study. In contrast, increasing load in the same temporal memory task had a much stronger effect on time intervals produced concurrently than increasing load in the spatial memory task [I wondered if the same effects would be obtained had the format been the same for the spatial & temporal tasks, i.e. if both tasks had required a translation from a digit to a position – what would the results be if in the spatial position task participants had been presented with [G, 2]?]. ~~-~~These results support an interpretation of the interference between timing and concurrent tasks in terms of specialized resources (Wickens, 1984, 1992) or memory subsystems (Baddeley, 1986; Baddeley, 2000; Baddeley & Hitch, 1974) as proposed by Brown (1997). Assuming that the temporal memory task mainly uses resources from the central-executive ~~principally~~ and that the spatial memory task relies mostly on a visuospatial subsystem, a stronger effect from processing temporal order on concurrent timing may be explained if timing uses resources associated with executive-control functions of working memory (Brown, 1997) but not spatial resources associated with a visuospatial memory subsystem. This conclusion is supported by Brown's data showing that visual search and spatial pursuit were not affected by concurrent temporal production. It ~~may~~ is also be interesting to note that in previous experiments, increasing the load in a visual search task did not lengthen simultaneous time productions whereas a lengthening was observed with corresponding manipulations in equally difficult item recognition tasks (Fortin, Rousseau, Bourque, & Kirouac, 1993). Taken together with the results of Experiment 1, these findings suggest that time production does not rely heavily on the use of visuospatial resources.

Another conclusion from the present study concerns the dissociation between the effects of processing and maintenance of information in memory on concurrent timing: ~~t~~The interference between searching for temporal order in memory and time estimation was clearly stronger than the interference caused by maintenance of temporal order information even though information must be maintained throughout the interval to be estimated. This is in line with ~~supports~~ previous results showing that ~~studies in which~~ passive retention in memory had no effect on concurrent time production (Field & Groeger, 2004, Exp. 2 and 3; Fortin & Breton, Exp. 1; Fortin & Massé, 1999, Exp. 2) and time discrimination (Rammsayer & Ulrich, 2005). In only two experiments was retention found to have an effect in similar tasks, one in which information on pitch (Field & Groeger, Exp. 1), and another in which durations of tones (Field & Groeger, Exp. 4) had to be remembered. One possibility mentioned to explain the effect of pitch retention on time production is that retaining pitch would involve more active processing than retention of other memoranda. This would be related to the potential of pitches to form a meaningful group of stimuli~~, a~~ or melody, which is less likely with other types of information. The effect of retaining duration of tone might be due to the fact that in this case, the information retained is identical to that processed in the timing task, that is, durations or time intervals. In the present study, the error data in Experiment 2 support this hypothesis in part because there was some effect of increasing load on accuracy in memory search when temporal order information was retained in the Probe-After condition. This effect might be explained by the similarity of information involved the memory and time production tasks. Finally, it must be noted that in one experiment, maintenance of visuospatial patterns was slightly ~~affected~~ disrupted by concurrent time discrimination (Rammsayer & Ulrich, 2005, Experiment 3) although time discrimination was not ~~perturbed~~ affected by the retention of visuospatial material. Taken together, these data suggest that timing is relatively undisturbed by concurrent maintenance of information in memory, except when this information has a clear temporal or sequential component [??].

To conclude, the results of the present study suggest that timing is especially dependent on resources also used in processing temporal order in memory. Given that processing temporal order involves processes generally associated with central executive functions (e.g., scheduling processes in dual-task situations), this is in agreement with previous studies relating timing to these functions (Brown, 1997; Rammsayer & Ulrich, 2005). It must be noted however that the duration values tested in the two experiments ~~was~~ were restricted to 2.7 (Experiment 1) and 2.0 s (Experiment 2). The relationship between memory functions might therefore be restricted to intervals around these values. However, ~~although~~ recent experiments showed similar effects from cognitive tasks on concurrent timing with intervals in the range of milliseconds (100 ms) and of longer duration (1000 ms) (Rammsayer & Ulrich, 2005). This suggests that results similar to those obtained in the present study could be obtained with timing tasks using ~~also~~ shorter durations.

Detailed analyses of disruptions in timing from interfering tasks such as those used in the present and other studies (e.g., Brown, 1997; Macar, 2002; Rammsayer & Ulrich, 2005) contribute to pinpoint the type of attentional resources involved when timing tasks are performed, a fundamental issue considering the central role of attention in most current influential models of timing (Gibbon, Church & Meck, 1984; Zakay & Block, 1996). Finally, from a practical perspective, given the use of timing tasks in measuring mental workload (e.g., Liu & Wickens, 1994), a more detailed definition of the processes involved in timing might also contribute to providing ~~e~~ a better index of the workload imposed by a variety of tasks (O’Donnell & Eggemeier, 1986).

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Table 1

Experiment 1. RT Condition: Mean RTs (ms) and Mean Percent Errors at each value of memory-set size in the spatial and temporal memory tasks

	Memory-Set Size			
	2		4	
Memory task	RT	Error	RT	Error
Spatial	668	5.05	834	6.95
Temporal	895	5.05	1041	6.99

Standard Errors of the Means (*SEM*) for RTs = 29.95, *SEM* for Percent Errors = 0.82 (Computed with a pooled Mean Square Error (*MSE*), see Loftus & Masson, 1994)

Table 2

Experiment 1. CP Condition: Mean Produced Intervals (PI) (ms) and Mean Percent Errors, at each value of memory-set size in the spatial and temporal memory tasks

	Memory-Set Size			
	2		4	
Memory task	PI	Error	PI	Error
Spatial	2767	2.21	2818	1.73
Temporal	2689	2.22	2784	3.40

SEM for PIs = 42.30, *SEM* for Percent Errors = 0.58 (Computed with a pooled *MSE*, see Loftus & Masson, 1994)

Table 3

Experiment 2. Mean Produced Intervals (PI) (ms) and mean percent errors in the Probe-In and the Probe-After Conditions, at each value of memory-set size

	Memory-Set Size					
	2		4		6	
Condition	PI	Error	PI	Error	PI	Error
Probe-In	2424	4.90	2538	8.34	2640	23.43
Probe-After	2267	4.69	2315	5.21	2333	17.60

SEM for PIs = 45.82, *SEM* for Percent Errors = 1.25 (Computed with a pooled *MSE*, see Loftus & Masson, 1994)

Figure caption

Figure 1. Experiment 1. Experimental trials in the RT condition with the spatial memory task (a), and the temporal memory task (b). Experimental trials in the Concurrent Processing (CP) condition when the spatial memory task (c) and the temporal memory task (d) were interpolated in a time interval production. Trials started either with simultaneous (a and c) or sequential (b and d) presentation of letters to be memorized. A fixation stimulus then appeared and remained on the screen until the participant pressed the “2” key, which triggered the presentation of the probe in the RT condition (a and b), and which began the interval production in the CP condition (c and d). The instructions were to press the “1” or the “3” key to indicate whether the probe’s spatial (a and c) or temporal (b and d) position represented correctly or not its position in the memory set. Participants were asked to respond to the probe as quickly as possible in the RT condition (a and b), and to respond when they judged that the target interval to be produced had elapsed in the CP condition (c and d).

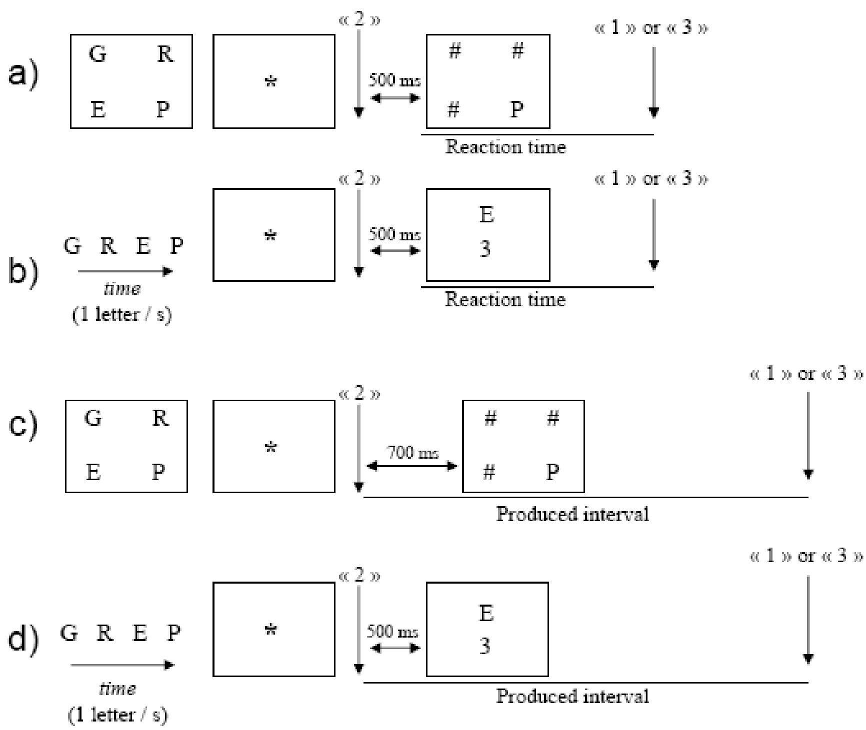
a)
G R
E P
*
« 2 »
500 ms
# #
P
« 1 » or « 3 »
Reaction time
b)
G R E P
time
(1 letter / s)
*
« 2 »
500 ms
E
3
« 1 » or « 3 »
Reaction time
c)
G R
E P
*
« 2 »
700 ms
# #
P
« 1 » or « 3 »
Produced interval
d)
G R E P
time
(1 letter / s)
*
« 2 »
500 ms
E
3
« 1 » or « 3 »
Produced interval

Figure 1