Timing, working memory and expectancy: a review of interference studies

Claudette Fortin¹ and Richard Schweickert²

¹École de psychologie, Université Laval, Pavillon Félix-Antoine Savard, 2325 rue des Bibliothèques, Québec, QC, Canada G1V 0A6

²Department of Psychological Sciences, Purdue University, 703 Third Street, West Lafayette, IN, USA 47907-2081, email: swike@psych.purdue.edu

Corresponding author: Claudette Fortin

École de psychologie, Université Laval, Pavillon Félix-Antoine Savard, 2325 rue des Bibliothèques, Québec, QC, Canada G1V 0A6

Email: claudette.fortin@psy.ulaval.ca

Phone: 00 1 418 928 9644

Abstract

Performing attention-demanding tasks concurrently with timing distorts estimated durations.

In studies reviewed, consistent interference between timing in the range of seconds and concurrent memory search was found, but no interference with visual search, switching or activation from long-term memory. We underscore the similarity between this pattern and results observed in research on complex span, a measure of working memory capacity.

According to an executive attention view of working memory capacity, high-working memory capacity individuals are better at maintaining goals, a useful ability in timing.

Another group of studies shows that expectancy interfered with timing, similarly to memory processing. Implicit timing is the source of interference in those studies, an influence that must be considered in timing studies on interference effects.

Introduction

Perceived duration of a stimulus is influenced by its duration and by other things such as valence or arousal [1-3], size [4,5], meaning [6], context [7,8], and concurrent tasks [9,10]. The influence of nontemporal features on estimated duration is often explained by attentional factors and tested in studies on the "interference effect". This refers to changes in perceived duration when demanding nontemporal processing is performed during duration estimation. Estimated durations typically range in seconds. The interference effect is one of the most consistent effects found in human timing studies [11]. Performing attention-demanding tasks concurrently with timing usually distorts estimated durations, but some processes do not interfere with timing. It was proposed that processes especially likely to interfere are executive processes such as coordination, integrating information and scheduling [12].

We begin by reviewing interference on timing from concurrent working memory processes, and then review interference from expectancy. Interference studies are highly task and stimulus sensitive [13,14], so we discuss studies in which participants are well trained at reproducing a single time interval. With precision and stability in timing performance thus achieved, influence of very specific manipulations is detected.

Timing and working memory: concurrent processing studies

The first studies contrast effects of various manipulations on concurrent time productions. In one study detailed below, increasing set size in a Sternberg memory task lengthened time intervals produced concurrently, whereas increasing set size in a visual search task did not. The conclusion was that memory search interrupted timing in the concurrent processing condition, but visual search did not. This logic is based on a prevalent information-processing model of timing as attention-controlled accumulation of temporal

information [15-19]. In this model, at the onset of an interval to be timed, an internal source of temporal information, a pacemaker, emits pulses transferred to an accumulator through an attention-controlled gate. The current pulse count in working memory is compared with a previously stored criterion in reference memory. When the count reaches the criterion, a decision is made about the time estimate, triggering a response ending the interval in time production. Since memory search lengthened concurrent time production, the interpretation was that timing is disrupted by concurrent memory search because both require some common resource, thus postponing the end of production as illustrated in Figure 1. In contrast, visual search did not interrupt the accumulation and was performed in parallel with timing [10,20].

In the studies reported below, error rates in nontemporal tasks concurrent with timing were equalized through feedback, eliminating a speed-accuracy trade-off explanation for different effects on concurrent timing.

Memory search and visual search. In a first study[20], four search tasks were executed in single-task RT control conditions and in concurrent timing conditions. Briefly, a participant was first trained at producing a given target interval (e.g., 2 seconds) by pressing a key twice. Then, in concurrent timing trials, the participant reproduced the target interval as precisely as possible. During the production, a probe to be searched for was presented. The participant ended the interval by pressing one of two keys to indicate whether the probe was present or absent. Therefore, during the interval production, the participant had to estimate time while executing the concurrent search task. Four tasks with varying degrees of memory demands were tested in four experiments: the Sternberg memory task with 1 to 6 items to be searched in memory, a search task where items 1 to 5 items presented visually were to be compared

with one memorized item, and two spatial attention visual search tasks with no memory requirements [21]. In all four tasks, increasing set size by one item increased mean RTs by about 40 ms in control RT conditions, so increasing size was about equally demanding in each task. However, when each task was interpolated in concurrent time production, the effect of increasing size varied drastically. The prolongation of time intervals produced concurrently was positively related to memory requirements in the search task. The conclusion was that interference of nontemporal processing on time processing may not be due to conflicting demand for general purpose attentional resources, but rather to specific concurrent short-term-memory processing demands [20]. It was concluded that an interference analysis of nontemporal and temporal processing should consider precisely which processes are involved in nontemporal processing [20].

In another study, time production was independent of varying load in memory search when the probe was presented immediately after the end of a time production, and was instead influenced by mental comparison of the probe when it occurred during the interval. This showed that the interference between memory search and timing was independent of the number of items maintained in short-term memory during timing. We concluded that working memory, defined as a work space for active processing of current information, contributes to time estimation, and that the interruption mechanism or the accumulation process is controlled by working memory processing without using storage capacity [22]. Further experiments supported this conclusion, showing that processing order-information in working memory, rather than maintenance of order, interfered with timing [23] and that the interference was not limited to processing verbal information in working memory [22,24]. This conclusion from our studies on working memory and timing supports recent findings and theoretical developments in neurobiology of timing [25].

Memory search and task switching. In other experiments, memory search and task switching were interpolated in time productions [26]. A pair of tasks, memory search and digit classification, was performed successively on each trial. There were four conditions: search-search (search followed by search), search-classify, classify-search and classify-classify. When responding to the second stimulus required a switch, concurrent time productions were unaffected, whereas increasing set size in memory search, within the same trial, lengthened productions. This intra-trial dissociation was observed with univalent task switching, with different stimuli in the two tasks (letters and digits in memory and classification tasks, respectively) [26] as well as with bivalent [27] task switching, with same stimulus set in both tasks. We concluded that switching is an executive function not interfering with timing, under conditions where memory search did interfere. Interestingly, a recent study found that verbal memory and two executive functions, planning and conditional inhibition, predicted variance in pre-attentive timing, but no significant relationship with task switching [28]. In a recent experiment [9], a task requiring task switching interfered with concurrent timing. The result is not contrary to our claim that task switching does not interfere with timing, because in each stimulus many copies of a small letter, e.g., A, were formed into a different large letter, e.g., B. Hence, the task also required considerable inhibition of an irrelevant dimension. Such inhibition in the Stroop task interferes with timing [9], and may have been the source of interference, not the switching.

Memory search and memory set activation. A recent study tested whether activating information from long-term memory would interfere with time production [29]. Participants memorized four memory sets (3 to 6 words) in a list-learning phase. During the subsequent time production, a probe was presented, with a digit indicating in which of the four memory

sets the probe had to be searched for. During the interval, the participant had to activate the set from long-term memory and then to search it. In half of the trials the digit was presented one second before the probe, allowing early activation. In a single-task RT control condition, increasing set size increased RTs by 198 ms. When there was no delay, so the memory set had to be activated before the probe could be used, RTs were 261 ms longer than when there was a delay. In the concurrent timing condition, increasing set size significantly lengthened produced intervals by 131 ms, whereas activation from long-term memory lengthened productions by 24 ms, a statistically nonsignificant effect. We concluded that memory search interfered with timing but activation from long-term memory did not.

Conclusion on concurrent processing studies. Results overall show that memory search consistently interferes with timing, whereas visual search, task switching and activating representations from long-term memory do not. There is a striking similarity between this pattern and results in complex span research [29]. Performance in memory search is related to complex-span [30], but performance in visual search, task switching [31], and memory set activation [30] are not.

Complex span is a measure of working memory capacity [32]. One performs an activity such as subtraction, stores an item; performs another activity and stores another item, continuing until the sequence is finished. The score is the number of items correctly recalled in correct serial positions [33]. Individuals with high-complex span perform better on various tasks than individuals with low complex-span. The executive attention view of working memory capacity [31,34] explains this by saying high-working memory capacity individuals are better at maintaining goals. Thus people with high complex span are more accurate at

timing [35]; a timing task demands maintaining the goal of estimating duration throughout its completion.

Expectancy and timing

A typical finding is that a concurrent task disrupts time estimation, whether or not there is any specific effect from the task. This nonspecific cost of concurrency may be attributed to coordinating tasks [11,16] or simply to interruptions in timing. To test the effect of interruptions independently of concurrent processing, Fortin & Massé introduced empty interruptions in time production [36]. Participants produced a well-learned time interval as in the experiments described above. To start time production, a tone was presented. The task was to press a key when the tone duration reached the practiced target duration (e.g., 2 seconds). The tone was briefly interrupted during its presentation, so participants had to estimate the tone duration before the break (or gap) in tone presentation, interrupt timing during the break, and resume timing when the tone resumed. When the target duration was estimated to be reached, participants ended the interval (Figure 2). In those experiments, the longer the duration preceding the break, the longer produced intervals were; note that produced interval is defined as the sum of prebreak and postbreak durations and excludes the break duration (Figure 3). This suggested that expecting the break onset signal interfered with an accumulation process in a fashion similar to interference in concurrent processing experiments. Importantly, when catch trials with no break were mixed with trials with breaks, longest intervals were produced in no-break trials, showing that longer productions were caused by expecting the break signal, not by the signal or the break itself (Figure 4).

The generality of this expectancy effect was demonstrated with various stimuli and paradigms [37-39]. It occurs with varying positions of intervening stimuli in time

discrimination [40]. It is stronger with older than younger adults [41], with visual than auditory stimuli [42], and when participants do not count to aid timing [43]. In short, when attention requirements are higher, effects of expectancy are stronger, which supports an attentional interpretation of the effect.

Expectancy effects occur in timing studies when participants are expecting something to happen, so it is highly probable that in timing studies with concurrent tasks, the mere expectancy of stimuli for the concurrent tasks perturbs timing.

Expectancy affects timing in a way similar to concurrent processing, leading to a similar interpretation in terms of disruption in accumulation of temporal information. However, there are important differences in studies. First, expectancy experiments involve implicit temporal preparation. Implicit timing is recruited when the regular temporal pattern of stimuli can be used to achieve nontemporal task goals [44,45]. In break experiments, the break onset signal is delivered at specific points during interval production; temporal preparation to interrupt timing as soon as the signal appears may lead to accurate time interval production. Implicit timing would thus occur before the break onset signal, without explicit instructions to try to predict its occurrence, concurrently with explicit timing required in the time production task.

In concurrent processing studies, participants are asked explicitly to execute two tasks, for example memory search and time production; attention sharing is deliberate, controlled, and effortful, resulting in longer produced intervals. In break experiments [41-43,46], produced intervals lengthen proportionally to the duration of expectancy for the break signal, but participants are unaware of sharing attention between timing and expecting the

signal. In break experiments, implicit, predictive timing is not related to production of a motor response, but only to interruption in timing, which eliminates the potential influence of motor preparation.

Implicit and explicit timing have almost always been examined independently, using very different paradigms [47]. A recent study [47] directly compared explicit and implicit conditions. A functional anatomy analysis revealed activation of a right-lateralised fronto-striatal network when timing was measured explicitly by a temporal reproduction task. Activation of left inferior parietal cortex, left premotor cortex and cerebellum was observed when temporal prediction was measured implicitly in a temporal orienting task, where participants predicted the offset of an externally specified time interval. Performances in explicit and implicit timing tasks were significantly correlated however, and common anatomical structures for explicit and implicit predictive timing were identified, namely right dorsolateral prefrontal cortex, bilateral inferior frontal gyri, pre supplementary motor area and inferior parietal cortices [47]. This correlation suggests common structures that might be involved in the interference found between implicit timing related to break expectancy and explicit time production. Break paradigm results show that within the same task, explicit estimation in time production and implicit timing may proceed concurrently and interact with each other (Figures 2, 3, 4).

Behavioural effects of increasing duration of expectancy and increasing duration of concurrent processing are similar, both lengthening time productions. Our analysis suggests that when concurrent tasks are executed during timing, both effects may be present: an effect of implicit temporal prediction related to the occurrence of the stimulus in the concurrent task in addition to the effect of concurrent processing. More generally, we conclude that implicit

and explicit timing, usually studied independently, interact in highly temporally structured environments such as timing experiments.

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Figure Captions

Figure 1. A schematic illustration of processes during time production in an accumulation framework. The participant begins the production by pressing a key (1). Accumulation of temporal information begins until a criterion amount of temporal information corresponding to the target interval is reached. Reaching the criterion (C1) triggers the decision to end of the interval by pressing a key (2.1). If during the interval some concurrent process requires resources also required by timing, accumulation is interrupted while the interfering process is executed, and then resumes. The interruption in pulse accumulation delays the time when the criterion is reached (C2) so the produced interval is longer (2.2) than in time production without interruption due to concurrent processing (2.1).

Figure 2. Time productions with no break and with break in timing. Accumulation begins with the first keypress (1) which proceeds in trial with no break until the criterion is reached (C1), which triggers the response ending the interval (2.1). In time production with break, accumulation begins (1), but its rate is slower before the break onset signal. Accumulation is interrupted and resumes at the break onset and offset respectively, and then proceeds until the criterion is reached (C2); this occurs later than in trials with no break (C1) because of the delays in accumulation due to slower accumulation before the break signal and its interruption during the break. In break experiments, the value of time production is obtained by subtracting the break duration from the interval between 1 and 2.2. since during the break, timing must be interrupted.

Figure 3. Time production in a trial where there is no break and no break is expected, and in trials with breaks. Note that duration of the break itself (time between break onset and offset as shown in Figure 2) is not represented in Figure 3. If a break signal is not expected and there is no break, accumulation begins at the first keypress (1), and proceeds until the criterion is reached (C1), which triggers the response ending the interval (2.1). In a trial with a break, if a break signal is expected, accumulation begins (1), but at a slower rate before the signal of break onset, which delays the time when the criterion is reached (C2), so that the end of time production is executed later (2.2). When the break signal occurs later, the period of slower accumulation is longer so the criterion is reached even later (C3) hence additional lengthening of produced interval (2.3).

Figure 4. Time production in trials with no break, when a break is not expected (C1) and when a break is expected (C2). In trials with no break, productions are much longer when a break is expected because accumulation is slower throughout the interval production, until the criterion is reached. In break experiments, longest intervals are produced when a break is expected during a time production but never occurs, showing that the lengthening is not due to the break itself but to its expectancy.

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Distinct patterns of neural activity were identified, although some commonalities were also noted.

Figure 1

Figure 1

Figure 2

Figure 2

Figure 3

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Figure 4