Attention sharing during timing: Modulation by processing demands of an expected stimulus

JULIE CHAMPAGNE AND CLAUDETTE FORTIN
Université Laval, Québec City, Québec, Canada

Varying the location of a nontemporal task during a time estimation task affects temporal estimates. Previous studies have also shown that manipulating the location of a stimulus to ignore may disturb timing similarly, suggesting that the effect might be independent of the processing requirements in the nontemporal task. In Experiment 1, the location of a tone varied during a 2-sec interval production; participants were asked either to ignore the tone or to discriminate its frequency. Productions were longer when the tone was presented later, but only when it was processed. In Experiment 2, short and long tones corresponding to more or less difficult discrimination tasks were used. The location effect was stronger and remained stronger throughout the experiment when participants were tested with the short tone in the first experimental session than when they were tested with the long tone first. These results suggest that timing is influenced by relatively stable attention-sharing strategies.

The dual-task paradigm has been widely used in studies to investigate the role of attention in prospective time estimation. In these studies, two main effects related to attention in human timing were observed. The first one is the *interference effect*, which shows that temporal performance is impaired when a nontemporal task diverts attention from timing (see Brown, 1997, for a review). More precisely, perceived time is usually shortened in relation to conditions in which timing is performed alone. Increasing difficulty of the nontemporal task typically leads to an increase of the interference effect (e.g., Brown, 1985, 1997; Brown & Bennett, 2002; Field & Groeger, 2004; Hicks, Miller, & Kinsbourne, 1976; Rammsayer & Ulrich, 2005; Zakay, Nitzan, & Glicksohn, 1983). The second main effect in timing that is interpreted by referring to attentional processes is the *location effect* (or *position effect*). This effect consists of a gradual shortening of a perceived time interval as a stimulus to be processed during this interval occurs later (Buffardi, 1971; Casini & Macar, 1997; Macar, 2002).

Both effects were interpreted similarly, in the context of an accumulation framework. Within this framework, time estimation is assumed to involve an accumulation of temporal units (*pulses*, in internal-clock models), the accumulation process being under attentional control (Gibbon, Church, & Meck, 1984; Zakay & Block, 1996). Accumulation would be disrupted when the temporal and the nontemporal tasks require attention concurrently (e.g., Brown, 1985, 1997; Hicks et al., 1976; Zakay, 1989, 2000). A reduced number of accumulated pulses would result in shorter perceived duration. Attention required in the nontemporal tasks would explain the interference effect (Brown, 1997). Attention shifts related to the expect-

tation of an upcoming stimulus would similarly disrupt temporal accumulation, the disruption being longer when the stimulus occurs later—hence the location effect (e.g., Macar, 2002).

However, some recent studies suggest that the attentional processes involved in the interference effect might differ from those involved in the location effect. Dual-task paradigms have shown that temporal underestimation results from increased concurrent mental load (Fortin & Rousseau, 1998; Sawyer, Meyers, & Huser, 1994) or when instructions emphasize that greater attention must be paid to the concurrent task (e.g., Casini & Macar, 1997; Macar, Grondin, & Casini, 1994). As noted by Macar (2002), these studies underscored the influence of controlled attention mechanisms in the interference effect. In contrast, recent results suggest that the location effect might be independent of processing demands that are related to the expected stimulus and could be induced by automatic shifts that are triggered by a stimulus that is completely irrelevant to the experimental task (Macar, 2002). This issue is of considerable interest, since a common view of attentional mechanisms involved in these two effects would provide a more parsimonious theoretical interpretation of attention-related perturbations in timing. With this perspective, we examined in the present study the issue of the independence of the location effect from processing demands related to the expected stimulus.

Varying the position of a stimulus to be processed during a timing task is one of the manipulations that, among others, seems to cause attentional disruptions. Generally, a time interval is judged as being shorter when the stimulus occurs later in the interval (Buffardi, 1971; Casini & Macar, 1997). In the production of time intervals, under-

J. Champagne, julie.champagne.1@ulaval.ca

estimation results in longer produced intervals, because when time is judged to be shorter, it takes longer to reach the subjective target duration and, consequently, to end the temporal interval. Therefore, when a stimulus to be processed is interpolated in time production, produced intervals become longer as the delay before stimulus presentation increases (e.g., Burle & Casini, 2001; Rousseau, Picard, & Pitre, 1984). This effect of stimulus location was also observed when the required response was to immediately interrupt timing when the stimulus appeared during interval production (Fortin, Bédard, & Champagne, 2005; Fortin & Massé, 2000).

Various combinations of timing and concurrent tasks have been used to investigate the location effect. It was observed in experiments in which the location of discrimination tasks was manipulated during a time production task (Burle & Casini, 2001; Rakitin, 2005; Rousseau et al., 1984), a time reproduction task (Macar, 2002), and a time discrimination task (Casini & Macar, 1997). It was also obtained in experiments in which the stimulus to be processed was a tone offset, which indicated to interrupt timing during a time production (Fortin & Massé, 2000) or time discrimination (Tremblay & Fortin, 2003) task. In all experiments, manipulating the location of the stimulus to be processed influenced temporal performance, so that time intervals were perceived to be shorter when the duration that had elapsed before the stimulus presentation was longer.

In those previous studies, the stimulus of which location was varied had to be processed, being, for example, a tone of which frequency had to be classified, or a tone offset which indicated to stop timing immediately. In two studies, trials in which participants were instructed to ignore the stimulus were included as control trials in order to test a possible effect of stimulus occurrence that was independent of any processing requirement. In some of these control trials, the location effect was observed, even though participants did not have to perform the discrimination task with the stimulus (as in experimental trials; Casini & Macar, 1997; Macar, 2002). The effect, when the stimulus was ignored, appeared to be inconsistent, however, since it was not observed in the same studies under some other conditions (Casini & Macar, 1997, Experiment 2; Macar, 2002). Nevertheless, the authors proposed two different hypotheses to explain a potential influence of a stimulus to ignore. One hypothesis was that even if the stimulus was irrelevant, participants might not have followed the instructions to ignore its presentation and would actually have processed it. Another hypothesis was that presenting a stimulus in a series of trials during a timing task could trigger automatic attentional shifts, whether this stimulus was processed or really ignored (Casini & Macar, 1997; Macar, 2002).

The first hypothesis is plausible, especially in the context of the Casini and Macar (1997) and Macar (2002) studies, because in those experiments, trials with the ignore instructions were sometimes performed after trials in which the same stimulus had to be processed. The hypothesis of automatic shifts caused by any stimulus presented during a timing task is also very plausible and interesting. Indeed, in the attentional time-sharing interpretation of

the location effect proposed in the literature, the characteristics of the shifts purportedly responsible for the effect have never been specified. It would therefore be highly informative to know whether these shifts are purely automatic or if they depend on the processing requirements related to the stimulus.

Although these observations in control conditions with stimuli to ignore suggested that automatic shifts could contribute to the location effect, the issue of a possible modulation of this effect by the processing demands of the intervening stimulus has never been tested directly. This was, therefore, the objective of the present study. In Experiments 1A and 1B, the influence of stimuli to be processed and to be ignored were compared, with these two conditions representing two values in terms of processing demands. In Experiment 2, a tone of which frequency was discriminated was used as in the process condition of Experiment 1B, but with two levels of difficulty and, consequently, of processing demands in the discrimination task.

In Experiment 1A, the location of a tone to be ignored was varied during a time production. This condition was tested alone, in the absence of any other condition in which the tone would have to be processed. This eliminated the possibility of a tendency to process the stimulus despite the instructions because of other trials in the experiment in which the stimulus would have to be processed. In Experiment 1B, two conditions were contrasted: a condition in which participants were asked to ignore the tone and a condition in which the tone had to be processed—that is, in which the tone frequency had to be discriminated. However, the stimulus in the ignore condition was different from that in the process condition in order to distinguish clearly the stimuli in the two conditions, thus avoiding any tendency to process inadvertently the stimulus to be ignored.

The duration of a tone to be discriminated was also varied in one experiment of Macar's (2002) study, the hypothesis being that the temporal characteristics of a stimulus—even if irrelevant—may be especially difficult to ignore in the context of a temporal task. In most conditions, intervals with the long tone were overestimated, suggesting, according to the author, that irrelevant stimuli can interfere with time processing. Varying the tone's duration in Experiment 2 of the present study will also permit us to examine this issue.

To summarize, we verified in Experiments 1A and 1B whether a location effect could be induced by any stimulus of varying location in time estimation, and whether the stimulus must be processed, which would suggest that this effect could be caused by automatic attention shifts. Experiment 2 provided a finer test of whether the effect could be modulated by processing demands that are related to the stimulus by using, as in Experiment 1B, a tone of which frequency had to be discriminated. In Experiment 2, however, the tone could be either very short or longer; because the longer tone was easier to discriminate than the shorter one, processing demands were lower in the long-tone than in the short-tone condition. The order in which participants were tested with the short and long

stimuli was counterbalanced, to allow us to find whether the location effect could be influenced by the order of testing under some conditions.

EXPERIMENT 1A

Experiment 1A was designed to verify whether the location effect could be induced by a stimulus to be ignored during a time interval production. The stimulus was always to be ignored by participants in this experiment, minimizing the possibility of confusion that could lead participants to process the stimulus inadvertently.

Method

Participants. Ten adults—6 men and 4 women between 18 and 36 years of age ($M = 24.00$, $SD = 4.85$)—took part in the experiment. They received a small honorarium of Can\$12 for their participation. They were naive to the experimental hypotheses.

Apparatus and Stimuli. Presentation of instructions, stimuli, and feedback, as well as data collection, were controlled by a PC using Micro Experimental Laboratory (MEL, Version 2) software. Visual stimuli were presented on a VGA color monitor (25×20 cm). Participants sat at a distance of approximately 1 m from the screen. Response times and time productions were measured to the nearest millisecond.

A 50-dB tone was presented during each trial and lasted for 150 msec. The frequency of the tone could be either 1020 Hz or 985 Hz.

Procedure. Participants were first trained to produce a 2-sec target interval in two practice sessions. Each session included five 48-trial blocks with a 30-sec pause between blocks. A trial began with the presentation of the word "Production" in the middle of the screen. When ready, participants pressed the space bar of the keyboard to begin producing the target interval, which caused the word "Production" to be replaced by a blank screen. The participants pressed the space bar a second time when they estimated the target interval to have elapsed. In the first four blocks, a visual feedback, "Too short," "Too long," or "Correct" (in French) appeared on the screen after each interval production, informing participants whether the produced interval was too short, too long, or correct, relative to the target interval. The feedback was displayed in the middle of the screen in white uppercase letters (height = 5 mm), on a black background. A time interval was considered correct if its value was within a 10% window centered on the target interval. The objective of providing feedback was to favor accuracy in interval production and to stabilize temporal performance. In the fifth (and last) block, there was no feedback after the interval. This way, participants also practiced producing intervals with no feedback, as they would be required to do later in the experimental trials. Overall, a practice session lasted approximately 25 min.

Practice sessions were followed by one experimental session. Before introducing experimental trials in that session, there were two 12-trial blocks of practice of time production: There was feedback on time production accuracy in the first of these two blocks, as in the first four practice blocks, whereas there was no feedback in the second block, as in the last practice block. The objective of these two blocks in the experimental session was to reset the memory representation of the target interval to be produced. After the first two blocks, there were six practice trials, in which a tone was presented during the interval production; the tone was presented in these trials in order to familiarize participants with the stimulus conditions of the following experimental trials. In these trials, participants were asked to produce the target interval while ignoring the tone. Experimental trials then followed in three 30-trial blocks, in which participants were again instructed to produce the target interval while ignoring the tone emitted during the interval. The experimental session lasted

for 20 min approximately. Only data from experimental trials were included in the analyses (i.e., data from the three 30-trial blocks).

At the beginning of each trial, the word "Production" appeared in the middle of the screen. When ready, the participants pressed the space bar to begin the interval production, which made the word "Production" disappear. A tone was emitted 450, 700, or 950 msec after the beginning of the interval production. Participants were asked to end the production by pressing either the "1" key or the "3" key on the numeric keyboard. The choice of key used to terminate the interval was left to the participant, but they were asked to use both keys as much as possible. The monitor screen was blank during the interval production.

Location and frequency of tone were varied within blocks of trials. On each trial, the values of location and frequency were selected randomly, with the constraints that there was an equal number of trials at each level of the location factor and that, at each level, the two tone frequencies were equally represented.

Results

Means and standard deviations of produced intervals were computed for each participant. Intervals that were longer or shorter than 3 SD s from the individual means were discarded; these represented 1.1% of the initial experimental data set.

Mean produced intervals were then computed as a function of the tone location (450, 700, and 950 msec) for each participant, and those means were submitted to a repeated measures ANOVA with one factor: the location of the tone.

Figure 1 shows mean time productions as a function of tone location. There was no increase of mean produced intervals as a function of the tone location; this was confirmed in the ANOVA [$F(2,18) = 1.16$, $p = .34$].

In the two practice sessions, mean intervals produced in the four blocks with feedback and in the block without feedback were, respectively, 1,990 msec ($SD = 25.2$) and 2,160 msec ($SD = 91.5$). In the experimental session, mean intervals produced in the block with feedback ($M = 2,049$ msec, $SD = 54.5$) and the practice block without feedback ($M = 2,088$ msec, $SD = 132.2$) showed that the temporal production performance was relatively precise and stable.

A paired sample t test (two-sided) conducted on mean produced intervals in the practice block (without feedback) of the experimental session and on mean intervals produced in ignored-tone experimental blocks ($M = 2,234$ msec, $SD = 334.6$) were not significantly different [$t(9) = -1.95$, $p > .05$].

Discussion

Mean produced intervals did not vary when the location of a tone to be ignored was manipulated during a temporal production in the present experiment. This result differs from the observation of a location effect in similar instruction conditions in previous studies (Casini & Macar, 1997; Macar, 2002). This might be explained by some differences in methodology between the two sets of studies. In particular, participants never had to process the stimulus in the present experiment, whereas, in previous studies, the stimulus had to be processed in some trial blocks. It is possible that in those experiments, it was difficult to in-

Figure 1. Experiment 1A: Mean produced intervals as a function of tone location. Error bars represent the standard errors of the means, computed with the mean square error (MS_e) (see Masson & Loftus, 2003).

hibit the processing of a stimulus to which some response was required in other trials. In contrast, the fact that the stimulus was never processed in the present experiment eliminated the possibility of some carryover of effects from one condition to another.

There was no difference between intervals produced in experimental trials and in corresponding practice trials; this supports the conclusion that participants ignored the tone of varying location in the experimental trials.

EXPERIMENT 1B

In Experiment 1B, the hypothesis that the location effect could be induced by any stimulus presented during an interval production was tested further, by comparing a condition in which participants were instructed to ignore the tone with a condition in which the instructions were to classify the tone as being high- or low-pitched.

Method

Participants. Sixteen adults—6 men and 10 women between 19 and 40 years of age ($M = 26.25$, $SD = 5.92$)—took part in the experiment. They received a small honorarium of Can\$12 for their participation.

Apparatus and Stimuli. The apparatus and software associated with this experiment were similar to those used in Experiment 1A, with the following exceptions. In the process condition, participants had to classify a tone as being high-pitched (1020 Hz) or low-pitched (995 Hz). In the ignore condition, a 350-Hz tone was emitted. In both conditions, the 50-dB tone lasted for 150 msec.

Procedure. Participants were first trained to produce a 2-sec target interval in two practice sessions, as described in the Method section of Experiment 1A. All participants were then tested in a single experimental session. There were six blocks of trials, and the order in which participants were tested in the two instruction conditions was counterbalanced. Half of the participants were thus asked to ignore and then to process the tone in the first three blocks and the last three blocks of trials, respectively; the other half of the participants were

tested in the reverse order. The participants were assigned randomly to the order condition (ignore–process or process–ignore). The location of the tone was manipulated in both instruction conditions.

There were six 30-trial blocks. In the ignore condition, the procedure was similar to that of Experiment 1A, but with two exceptions. First, a single tone frequency was associated with this condition (350 Hz), so that the tone was clearly different from the tone used in the process condition (1020 Hz or 995 Hz). This minimized the possibility of confusion that might lead the participants to process accidentally the tone in the ignore condition. Second, the key used to end the interval production was the “0” key on the numeric keyboard.

In the process condition, participants were instructed to produce the target interval while simultaneously discriminating the tone on the pitch dimension. The beginning of a trial was indicated by the presentation of the words “production + discrimination” in the middle of the screen. When ready, participants pressed the space bar to begin the temporal production, which was followed 450, 700, or 950 msec later by a tone presentation. The participants ended the interval production by pressing the “3” key to classify the tone as being high-pitched or the “1” key to classify the tone as being low-pitched. At the end of each trial, visual feedback informed participants whether their discrimination response was correct or not (“Correct” or “Error,” in French). Just before the three blocks in the process condition, participants performed 20 trials of the discrimination task alone and 20 trials of discrimination interpolated in time production. The experimental session lasted approximately 40 min.

Results

Trials with an error in the discrimination task were discarded, which corresponded to 15.14% of the data in the process condition. Produced intervals that were longer or shorter than ± 3 SDs from the individual means were discarded, which represented 0.82% and 0.69% of the data in the ignore and process conditions, respectively. Mean intervals produced by each participant as a function of tone location (450, 700, and 950 msec) and instruction condition (process, ignore) were then computed, and those means were submitted to analyses. When, for a given effect, the Mauchly test for sphericity was significant at an

alpha value of .01, the p value obtained with the Huynh-Feldt correction was used. For simplicity of presentation, however, we report uncorrected degrees of freedom.

A first ANOVA was performed to verify whether the order in which the participants were tested influenced temporal judgments. Since order had no significant effect on produced intervals ($F < 1$) and did not interact with tone location, instruction conditions, or the interaction between location and instruction (all F s < 1), a second ANOVA was performed with data averaged over the two orders of testing, with two factors, tone location and instruction condition.

As shown in Figure 2, mean produced intervals lengthened as a function of the location value, but this effect was much stronger in the process-instruction than in the ignore-instruction condition. This was confirmed in the ANOVA, which revealed a significant effect of tone location [$F(2,30) = 7.77, p = .01$], and, more importantly, a significant interaction between location and instruction conditions [$F(2,30) = 5.38, p = .006$]. An analysis of simple main effects with a Bonferroni adjustment showed that the location effect was significant in the process-instruction condition [$F(2,30) = 9.38, p < .025$], but not in the ignore-instruction condition [$F(2,30) = 3.51, p > .025$]. Moreover, a paired sample t test (two-sided) revealed that the slope of the function in the process condition (0.29 msec/msec) was significantly stronger than the slope of the function in the ignore condition (0.12 msec/msec) [$t(15) = 2.84, p < .05$]. Finally, mean produced intervals were significantly longer in the process-instruction condition than in the ignore-instruction condition [$F(1,15) = 5.38, p = .035$].

In the two practice sessions, mean intervals produced in the four blocks with feedback and in the block without

feedback were, respectively, 1,988 msec ($SD = 29.3$) and 2,246 msec ($SD = 197.1$). In the experimental session, mean intervals produced in the block with feedback ($M = 2,018$ msec, $SD = 99.5$) and in the practice block without feedback ($M = 2,162$ msec, $SD = 152.2$) showed that participants were able to produce relatively precise and stable time intervals around the target duration.

As in Experiment 1A, mean produced intervals in practice trials (without feedback) of the experimental session and mean produced intervals in the ignore-instruction condition ($M = 2,136$ msec, $SD = 361.46$) were not significantly different; this was confirmed by a paired sample t test (two-sided) [$t(15) = 1.10, p > .05$].

Discussion

The primary finding of this experiment was the interaction between the location and instruction condition, which revealed that the effect of location was significantly stronger in the process than in the ignore condition. This result confirms that the location effect is dependent on processing demands that are related to the stimulus of which location is varied. The location effect seems therefore not to be a result of automatic shifts taking place before the occurrence of any stimulus of which location varies during a time estimation task.

It could be argued that, with regard to the location effect, the difference between the two instruction conditions might be related to the use of tones of quite different frequencies—350 Hz in the ignore condition and 1020 Hz or 995 Hz in the process condition. However, very similar tones (1020 Hz and 985 Hz) were used in the ignore condition of Experiment 1A with no effect of tone location,

Figure 2. Experiment 1B: Mean produced intervals as a function of the tone location in the ignore-instruction and the process-instruction conditions. Error bars represent the standard errors of the means, computed with the pooled MS_e (see Masson & Loftus, 2003).

demonstrating that tones in this range of frequencies could also be ignored in certain conditions.

Produced intervals were longer in the process than in the ignore condition, suggesting that tone discrimination interferes with timing. This interference effect (Brown, 1997) concerns the processing of the tone itself and affects the intercepts of the production functions shown in Figure 2. This effect is independent of the location effect, which concerns the expectation of the tone and affects the slopes of the functions shown in Figure 2. The interference effect reveals that discriminating the tone interrupts the accumulation of temporal information. To compensate for this loss, an additional amount of temporal information is needed in order to reach the criterion that corresponds to the target interval to be produced, resulting in longer produced intervals. Showing shorter productions in the ignored-tone condition supports the assumption that participants ignored the tone, which was in agreement with the instructions. It is worth noting that, as in Experiment 1A, there was no significant difference between intervals produced in the experimental trials in the ignore condition and those produced in the corresponding practice trials; this further supports the conclusion that participants ignored the tone in experimental trials.

EXPERIMENT 2

In Experiment 2, processing demands in tone discrimination were manipulated again in the location paradigm. However, the tone always had to be processed, and demands related to this processing were varied by manipulating the tone's duration. A very short tone and a longer one were used in a pitch discrimination task. If processing demands related to the stimulus affect the location effect, it might be expected that a very short tone—which is more difficult to discriminate—would lead to a stronger location effect than would a longer tone. Two main conditions were thus compared: one using a 10-msec tone and one using a 150-msec tone.

Method

Participants. Twenty-three adults—11 men and 12 women between 19 and 34 years of age ($M = 22.6$, $SD = 3.8$)—took part in the experiment. They received a small honorarium of Can\$15 for their participation.

Apparatus and Stimuli. The apparatus and software used in this experiment are the same as those used in Experiments 1A and 1B. As in Experiment 1B, participants had to classify a tone as being higher pitched (1020 Hz) or lower pitched (1000 Hz). The 55-dB tone lasted 10 msec in the short-tone condition and 150 msec in the long-tone condition.

Procedure. All participants were tested in short- and long-tone conditions in two separate experimental sessions. The order in which the participants were tested with the two durations was counterbalanced, so that half of the participants were tested in a first experimental session with the short tone, and then with the long tone in a second experimental session (S–L order), whereas the other half of the participants was tested in the reverse order (L–S order). The participants were assigned randomly to each order condition (S–L or L–S).

Participants were trained to produce a 2-sec target interval in two practice sessions, as described in Experiment 1A. Participants then

completed two experimental sessions, in which a tone occurred during the time interval production. The instructions and sequence of events in each experimental trial were identical to those in the process-instruction condition of Experiment 1B. Twenty trials of discrimination alone, and then 12 trials in the discrimination-with-time-production condition, were performed by participants before they began the experimental blocks of trials. Five 36-trial blocks were performed in each experimental session. The two tone duration conditions were varied between sessions.

Results

Data from 3 participants could not be used because, in at least one of the experimental conditions, their percentage of errors in the discrimination task was higher than 50%, suggesting that these participants had responded randomly. Trials with an error in the discrimination task were eliminated from the analyses, which represented 19.73% of the data in the short-tone condition and 15.72% of the data in the long-tone condition. A t test for paired samples (two-sided) showed that the error rate was significantly higher in the short-tone than in the long-tone condition [$t(19) = 2.59$, $p = .02$].

As in Experiments 1A and 1B, produced intervals longer or shorter than 3 SDs from the individual means were eliminated, which resulted in 0.2% of the data removed in the short-tone condition and 0.01% of the data removed in the long-tone condition. Mean intervals produced by each participant at each combination of values of tone location and tone duration were submitted to analyses. As in Experiment 1B, corrected p values are reported when the Mauchly test for sphericity was significant at .01.

Figure 3 shows mean produced intervals as a function of increasing values of tone location in the two order conditions (L–S, S–L); in each order condition, two functions show mean produced intervals in the short-tone and long-tone conditions separately. Mean produced intervals lengthened generally as a function of increasing values of tone location, but the effect seemed stronger in the S–L order condition than in the L–S order condition—that is, stronger when the short tone was used in the first experimental session than when the long tone was used in the first session.

An ANOVA with tone duration (short or long) and tone location (450, 700, 950 msec) as repeated factors, and with order of conditions (S–L, L–S) as a nonrepeated factor, was performed in order to test these observations. The analysis confirmed the general effect of tone location on mean produced intervals [$F(2,36) = 18.95$, $p < .001$]. The interaction between tone location and order of conditions was significant, however [$F(2,36) = 5.37$, $p = .02$], confirming that the effect of varying location was not equivalent in the two order conditions. Tests for simple main effects showed that time productions lengthened significantly as a function of tone location in both conditions [S–L, $F(2,18) = 13.43$, $p = .003$; L–S, $F(2,10) = 6.07$, $p = .01$] with a Bonferroni correction to the alpha level. The effect of location was nevertheless stronger in the S–L condition than in the L–S condition, since slopes of produced intervals as a function of location values were, on average, 0.36 msec/msec in the S–L condition and 0.11 msec/msec, on average, in the L–S condition.

Figure 3. Experiment 2: Mean produced intervals as a function of tone location and tone duration (short, long) in the two presentation orders of conditions (L-S, S-L). Error bars represent standard errors of the means computed with a pooled MS_e of within-subjects factors (see Masson & Loftus, 2003).

There was also a significant interaction between duration of tone and order [$F(2,18) = 6.54, p = .02$]. Indeed, the long tone led to longer produced intervals than did the short tone in the L-S order condition, whereas the short tone led to longer produced intervals than did the long tone in the S-L condition. Produced intervals were significantly longer in the long-tone condition than in the short-tone condition in the L-S condition [$t(9) = 3.04, p = .01$], but the difference in the S-L condition was not statistically significant [$t(9) = 1.13, p = .29$]. All other effects in the ANOVA were nonsignificant: tone duration; order of conditions; the interaction between location and duration; and the three-way interaction between location, tone duration, and order (all $F_s < 1$).

In the two practice sessions, mean intervals produced in the four blocks with feedback and in the block without feedback were, respectively, 1,979 msec ($SD = 26.6$) and 2,187 msec ($SD = 162.4$). In the short-tone condition, mean intervals produced in the practice block with feedback and in the practice block without feedback were, respectively, 2,026 msec ($SD = 108.6$) and 2,141 msec ($SD = 219$). In the long-tone condition, mean intervals produced in the practice block with feedback and in the practice block without feedback were, respectively, 2,063 msec ($SD = 98$) and 2,135 msec ($SD = 128.5$).

Discussion

The primary finding in Experiment 2 was the clear modulation of the location effect by the order in which

participants were tested with short and long tones: Varying location of a tone to discriminate had a stronger effect when participants were tested first with a short tone than when they were tested first with a long tone. The discrimination task was more difficult with the short tone, as revealed by the higher error rate in the short- than in the long-tone condition. It seems, therefore, that the effect of varying location of the discrimination task during timing was influenced by the level of difficulty of this task. This influence seemed to determine performance quite durably, so that even though discrimination was easier or more difficult later during the experiment, the effect of varying its location remained about the same.

The effect of discrimination difficulty on the location effect is in agreement with previous results. In some experiments, in which comparable short or long tones were used, the location effect was stronger with a short tone than with a longer one (Pitre, 1983). However, because the two tones were tested in separate experiments, the modulating action of testing order could not be observed in that study.

We may explain the stronger location effect when participants begin the experiment with the shorter tone as being due to more frequent attention shifts in order to monitor the source from which the signal comes; this would be due to a greater probability of missing the tone when a very short tone is used than when a longer tone is used. This interpretation was proposed by Pitre (1983) to explain a stronger effect of location with a short tone.

The effect of testing order extends these conclusions by suggesting that, once acquired, this mode of monitoring would be relatively stable.

There was an interaction between tone duration and order, so that when the long tone was used in the first experimental session (L–S condition), produced intervals were longer with the long tone than with the short tone. The opposite was observed when the short tone was used in the first experimental session (S–L condition). This shortening of time productions from the first to the second session, independent of tone duration, may reflect a general increase in training and familiarity with the task, which causes participants to produce time intervals closer to the 2-sec target interval in the second experimental session than in the first one. Indeed, after a first experimental session including training trials and experimental trials in the dual-task condition, participants were again, in the second experimental session, exposed to training trials with and without feedback on temporal accuracy just before executing the dual task. This may explain why their temporal productions were more accurate in the second session than in the first experimental session.

GENERAL DISCUSSION

The experiments of the present study were designed to examine whether the demands related to a discrimination task performed during a temporal production affect the magnitude of the location effect. Produced intervals were lengthened proportionally to the delay between the beginning of the interval production and the onset of the tone to process in the discrimination task, but only when the tone had to be processed, and not when participants were instructed to ignore the tone. Although this effect with the processed stimulus confirms results from numerous studies (e.g., Casini & Macar, 1997; Fortin & Massé, 2000; Macar, 2002), the absence of influence from a stimulus to be ignored seems to contradict previous findings that showed a similar effect with a stimulus that participants were asked to ignore (Macar, 2002). This apparent discrepancy may be explained, however, by an effect of carryover across identical conditions, in which participants had to process the stimulus and then, in later trials, had to ignore the same stimulus in Macar's study. There was no effect of testing order in Experiment 1B of the present study, which may be explained by the fact that quite different stimuli were used in the two instruction conditions: The tone frequency was clearly lower in the ignore condition than in the process condition, and the response keys associated, respectively to these conditions were different. In addition to eliminating possible confusion between the instruction conditions, this obvious difference minimized the probability of carryover in responding from one condition to another.

A clear effect of varying stimulus location was found when the stimulus had to be processed in all experiments. The location effect is usually interpreted as being a result of attention sharing between timing and processes related to expecting the signal, of which location is varied. This is

similar in essence to the interpretation commonly offered to explain the interference effect in timing (Brown, 1997). Timing would rely on accumulating temporal information—*pulses* in internal-clock models—and the accumulation process would be perturbed when some concurrent task also requires attention. This general interpretation 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 et al., 1994; Zakay et al., 1983) or to the proportion of attention deliberately allocated to nontemporal features of a stimulus (Casini & Macar, 1997; Coull, Vidal, Nazarian, & Macar, 2004). It also accounts for the location effect, since it is interpreted in previous studies as being a result of attention sharing between accumulating temporal information and monitoring for the stimulus occurrence. This would cause some micro-interruptions in the accumulation process when attention is not directed toward timing (e.g., Casini & Macar, 1997; Fortin, 2003; Macar, 2002; Rousseau et al., 1984), which slows down the accumulation process by causing a relative loss of temporal information. The loss would be proportional to the duration of attentional time-sharing. More time is needed to reach the criterion number of temporal information associated with the target interval to be produced—hence, longer produced intervals with increasing duration of time sharing. In time production, the slope of the function relating produced intervals to stimulus location may be taken as an index of the strength of the location effect and, within an attention-sharing interpretation, as an index of the frequency or duration of attention shifts (see Fortin, 2003). A steeper slope would correspond with a stronger location effect obtained because of longer or more frequent shifts of attention during timing.

Results from the present study suggest that the number or duration of shifts is influenced by processing demands related to the stimulus to come: Shifts would be more frequent or longer when participants are instructed to process the stimulus than when they are instructed to ignore it. Shifts would also be more frequent or longer when participants are tested first under conditions in which processing demands related to the stimulus are higher, as in the discrimination task of Experiment 2. Furthermore, the effect appeared to be stable, even when processing demands were reduced or increased in a following experimental session. Note that we observed such stability when participants were tested with a discrimination task of a given level of difficulty during a whole experimental session. Indeed, participants performed a large number of experimental trials with either the more or less demanding discrimination task in the first experimental session, which may have favored the establishment of a stable monitoring pattern.

This observation may be related to previous studies showing the influence of strategies adopted by participants as a function of difficulty of initial training in stimulus discrimination. In a previous study, when exposed to a range of discrimination difficulty, participants who were exposed first in a hard-discrimination condition showed higher sensitivity in visual discrimination than did par-

ticipants who were given initially easy discriminations (Doane, Alderton, Sohn, & Pellegrino, 1996). The interpretation for this result was that participants in the hard-first condition had developed a more precise comparison strategy in initial training than did participants in the easy-first condition, a strategy that they used throughout the experiment and which led to superior performance at transfer, when easier discrimination conditions were introduced. In the present experiment, the transfer does not concern the *discrimination task* itself, but the *attention-sharing processes* preceding the stimulus arrival. Participants adopted an attention-sharing strategy adapted to task difficulty, a strategy they used in the second experimental session as well. Attentional weighting is one of the main mechanisms of perceptual learning, by which attention paid to important dimensions in a task is modulated (Goldstone, 1998). In Experiment 2, more attention was allocated to monitoring for tone occurrence when the imminent stimulus was harder to discriminate, and this strategic choice was maintained in the second experimental session, despite the easier discrimination conditions.

The absence of a significant location effect in the ignore condition in Experiments 1A and 1B is not compatible with the hypothesis that manipulating the location of any expected stimulus would induce automatic attentional shifts, as suggested by Casini and Macar (1997) and Macar (2002). Nevertheless, attentional shifts do not appear to be under complete control, since, in Experiment 2, the shifting pattern acquired in the initial phase of the experiment seemed difficult to inhibit, persisting in a succeeding session even though the constraints associated with the interfering stimulus were changed.

To summarize, the present study showed that the location effect cannot be induced by purely automatic shifts triggered by any stimulus whose appearance is expected during a timing task, whether this stimulus must be processed or not. Furthermore, when the stimulus must be processed, the location effect may be sensitive to processing demands related to this stimulus. A parallel may be drawn between the modulating action of demands in tone discrimination on the effect of location found in the present study and the influence of task difficulty on the interference effect often observed in timing research. A higher level of difficulty in a nontemporal task is usually associated with stronger interference on concurrent time estimation (e.g., Brown, 1997; Brown & Bennett, 2002). Similarly, processing demands in a tone discrimination task of varying location might influence the location effect in timing. This supports the assumption that common attentional mechanisms underlie both effects. A second new and important finding in the present study is that the pattern of monitoring assumed to generate the location effect may be relatively stable, once acquired. This implies that the order in which the experimental conditions are administered within this paradigm may be critical. This might be especially true when, as in Experiment 2 of the present study, there is relatively extended practice in the respective conditions in distinct experimental sessions.

AUTHOR NOTE

This work was supported by scholarships to J.C. from the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Fonds pour la Formation de Chercheurs et l'Aide à la Recherche, and by a grant to C.F. from NSERC. Special thanks to Françoise Macar for thoughtful discussions on the data. We are also grateful to Charles Collyer and two anonymous reviewers for their helpful comments on a previous version of this article. We thank Marie-Eve Couture, Cathia Dutil, Marie-Eve Genest, Mélanie St-Laurent, and Paule Ellefsen Gauthier for their help in data collection. Correspondence concerning this article should be addressed to J. Champagne, École de Psychologie, Université Laval, Québec, QC, G1K 7P4 Canada (e-mail: julie.champagne.1@ulaval.ca).

REFERENCES

- BROWN, S. W. (1985). Time perception and attention: The effects of prospective versus retrospective paradigms and task demands on perceived duration. *Perception & Psychophysics*, **38**, 115-124.
- BROWN, S. W. (1997). Attentional resources in timing: Interference effects in concurrent temporal and nontemporal working memory tasks. *Perception & Psychophysics*, **59**, 1118-1140.
- BROWN, S. W., & BENNETT, E. D. (2002). The role of practice and automaticity in temporal and nontemporal dual-task performance. *Psychological Research*, **66**, 80-89.
- BUFFARDI, L. (1971). Factors affecting the filled-duration illusion in the auditory, tactual, and visual modalities. *Perception & Psychophysics*, **10**, 292-294.
- BURLE, B., & CASINI, L. (2001). Dissociation between activation and attention effects in time estimation: Implications for internal clock models. *Journal of Experimental Psychology: Human Perception & Performance*, **27**, 195-205.
- CASINI, L., & MACAR, F. (1997). Effects of attention manipulation on judgments of duration and of intensity in the visual modality. *Memory & Cognition*, **25**, 812-818.
- COULL, J. T., VIDAL, F., NAZARIAN, B., & MACAR, F. (2004). Functional anatomy of the attentional modulation of time estimation. *Science*, **303**, 1506-1508.
- DOANE, S. M., ALDERTON, D. L., SOHN, Y. W., & PELLEGRINO, J. W. (1996). Acquisition and transfer of skilled performance: Are visual discrimination skills stimulus specific? *Journal of Experimental Psychology: Human Perception & Performance*, **22**, 1218-1248.
- FIELD, D. T., & GROEGER, J. A. (2004). Temporal interval production and short-term memory. *Perception & Psychophysics*, **66**, 808-819.
- FORTIN, C. (2003). Attentional time-sharing in interval timing. In W. H. Meck (Ed.), *Functional and neural mechanisms of interval timing* (pp. 235-259). Boca Raton, FL: CRC Press.
- FORTIN, C., BÉDARD, M.-C., & CHAMPAGNE, J. (2005). Timing during interruptions in timing. *Journal of Experimental Psychology: Human Perception & Performance*, **31**, 276-288.
- FORTIN, C., & MASSÉ, N. (1999). Order information in short-term memory and time estimation. *Memory & Cognition*, **27**, 54-62.
- FORTIN, C., & MASSÉ, N. (2000). Expecting a break in time estimation: Attentional time-sharing without concurrent processing. *Journal of Experimental Psychology: Human Perception & Performance*, **26**, 1788-1796.
- FORTIN, C., & ROUSSEAU, R. (1998). Interference from short-term memory processing on encoding and reproducing brief durations. *Psychological Research*, **61**, 269-276.
- GIBBON, J., CHURCH, R., & MECK, W. H. (1984). Scalar timing in memory. In J. Gibbon & L. Allan (Eds.), *Timing and time perception* (Annals of the New York Academy of Sciences, Vol. 423, pp. 52-77). New York: New York Academy of Sciences.
- GOLDSTONE, R. L. (1998). Perceptual learning. *Annual Review of Psychology*, **49**, 585-612.
- HICKS, R. E., MILLER, G. W., & KINSBOURNE, M. (1976). Prospective and retrospective judgments of time as a function of amount of information processed. *American Journal of Psychology*, **89**, 719-730.
- MACAR, F. (2002). Expectancy, controlled attention and automatic attention in prospective temporal judgments. *Acta Psychologica*, **111**, 243-262.

- MACAR, F., GRONDIN, S., & CASINI, L. (1994). Controlled attention sharing influences time estimation. *Memory & Cognition*, **22**, 673-686.
- MASSON, M. E. J., & LOFTUS, G. R. (2003). Using confidence intervals for graphically based data interpretation. *Canadian Journal of Experimental Psychology*, **57**, 203-220.
- PITRE, E. (1983). *An on-off Poisson counter model and the effect of attention sharing on empty discrete temporal interval productions*. Unpublished doctoral dissertation, Université Laval.
- RAKITIN, B. C. (2005). The effects of spatial stimulus-response compatibility on choice time production accuracy and variability. *Journal of Experimental Psychology: Human Perception & Performance*, **31**, 685-702.
- RAMMSAYER, T., & ULRICH, R. (2005). No evidence for qualitative differences in the processing of short and long temporal intervals. *Acta Psychologica*, **120**, 141-171.
- ROUSSEAU, R., PICARD, D., & PITRE, E. (1984). An adaptive counter model for time estimation. In J. Gibbon & L. Allan (Eds.), *Timing and time perception* (Annals of the New York Academy of Sciences, Vol. 423, pp. 639-642). New York: New York Academy of Sciences.
- SAWYER, T. F., MEYERS, P. J., & HUSER, S. J. (1994). Contrasting task demands alter the perceived duration of brief time intervals. *Perception & Psychophysics*, **56**, 649-657.
- TREMBLAY, S., & FORTIN, C. (2003). Break expectancy in duration discrimination. *Journal of Experimental Psychology: Human Perception & Performance*, **29**, 823-831.
- ZAKAY, D. (1989). Subjective time and attentional resource allocation: An integrated model of time estimation. In I. Levin & D. Zakay (Eds.), *Time and human cognition: A life-span perspective* (pp. 365-397). Amsterdam: North-Holland.
- ZAKAY, D. (2000). Gating or switching? Gating is a better model of prospective timing (A response to "Switching or gating?" by Lejeune). *Behavioural Processes*, **50**, 1-7.
- ZAKAY, D., & BLOCK, R. A. (1996). The role of attention in time estimation processes. In M. A. Pastor & J. Artieda (Eds.), *Time, internal clocks and movement* (pp. 143-164). Amsterdam: Elsevier.
- ZAKAY, D., NITZAN, D., & GLICKSOHN, J. (1983). The influence of task difficulty and external tempo on subjective time estimation. *Perception & Psychophysics*, **34**, 451-456.

(Manuscript received February 15, 2007;
revision accepted for publication November 19, 2007.)