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Timing During Interruptions in Timing

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Duration and location of breaks in time interval production were manipulated in various conditions of stimulus presentation (Experiments 1–4). Produced intervals shortened and then stabilized as break duration lengthened, suggesting that participants used the break as a preparatory period to restart timing as quickly as possible at the end of the break. This interpretation was supported in Experiment 5, in which similar results were obtained with a reaction time response executed at the end of the break. In all experiments, produced intervals lengthened as the break occurred later during the interval. The authors conclude that varying break location and duration reveal, respectively, the influence of attentional time-sharing before the interruption and of preparatory processes taking place during the break.

It is well known that a period of time may seem longer or shorter depending on one's attention being oriented to the passage of time or to some distracting activity. The relation between attention and time estimation has been acknowledged for more than a century in psychology (James, 1890) and has been confirmed in studies showing systematic distortions in perceived time caused by concurrent performance of some other tasks that involve attention (e.g., Brown, 1985, 1997; Macar, 2002; Macar, Grondin, & Casini, 1994; McClain, 1983; Thomas & Weaver, 1975; Zakay, Nitzan, & Glickson, 1983).

The role of attention in timing has also been studied in a time production task with breaks with no concurrent task. In this procedure, participants press a key when a target duration has elapsed after the start of a tone presentation. There is a silent break in tone presentation in experimental trials, so that participants must interrupt and restart timing during the interval production. In this task, participants end the interval later when the break occurs later, suggesting a shortening of perceived tone duration while the break signal is expected. This has been confirmed in trials with no breaks, when a break is expected but does not occur, because longest productions were then produced (Fortin, 2003; Fortin & Massé, 2000). This suggests that when a break is expected, attention is shared between timing and monitoring the source of the break signal. Assuming that timing involves accumulating temporal information (Gibbon, Church, & Meck, 1984), which requires attention (e.g., Zakay & Block, 1996), attention sharing would result in loss of accumulated temporal information and, hence, shorter perceived duration (see also Casini & Macar, 1997; Rousseau, Picard, & Pitre, 1984).

In addition to break expectancy, other aspects of time production with breaks may also be affected by attention-related factors. As discussed below, manipulating break duration may reveal that the break is used as a preparatory period to restart timing. Manipulating stimulus conditions (e.g., breaks empty vs. filled with a stimulus) may show that in addition to affecting the attracting properties of the break signal (Buhusi & Meck, 2000), these conditions interact with preparatory processes taking place during the break. Therefore, break duration and stimulus conditions were manipulated in the present study to examine further the influence of attention in time production with breaks.

In the standard condition of this task, a tone presentation starts on the first keypress. Participants press the key again when they judge that the tone was presented for the target duration. During the break in tone presentation, participants must interrupt timing, which is restarted when the tone resumes. Results from previous studies suggest that restarting timing may be influenced by attentional manipulations. For example, the latency to start timing seems to be influenced by cues used to anticipate the modality of the stimulus to be timed (Meck, 1984). Because of the limited number of possible break durations in time production, participants can anticipate the time to resume timing at the end of the break. The break would then be used as a preparatory period to restart timing as soon as the signal ending the break is presented.

The issue of anticipating a signal to which one must react has been studied extensively in reaction time studies in which the *foreperiod*, that is, the time between a warning signal and the reaction signal, is manipulated. Effects of foreperiod differ depending on numerous factors (Niemi & Näätänen, 1981). When equally likely foreperiods vary from trial to trial, the usual result is that the larger the foreperiod, the shorter the mean reaction time (e.g., Drazin, 1961; Elliott, 1973; Requin, Granjon, Durup, & Reynard, 1973; for a review, see Luce, 1986). One interpretation proposed to explain this result is that as time elapses during the foreperiod, the probability of the signal's immediate occurrence increases, given that it has not already occurred. Participants learn to use this objective increase in probability because readiness to respond to the signal is more likely to be rewarded as time elapses during the foreperiod. Increasing readiness leads to shorter reaction times, which explains the negative reaction time–foreperiod relation (Elithorn & Lawrence, 1955; Requin & Granjon, 1969).

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If the break is also used as a foreperiod, the latency to restart timing at the end of the break should be longer with shorter breaks. Longer latency to restart timing would delay the end of the subjective interval, and hence result in longer productions. As in reaction time studies, productions should then be negatively related to break durations. In the present study, break duration was varied in order to test this hypothesis.

The characteristics of the stimulus presented during the prebreak and postbreak periods are also likely to influence performance. These periods are those that participants are explicitly required to time. There is ample evidence that nontemporal properties of a stimulus influence attentional processes (e.g., Bertelson & Tisseyre, 1969; Posner, Nissen, & Klein, 1976) as well as perceived duration in timing tasks. For example, an interval filled with a stimulus is judged to be longer than an empty interval of equal duration (e.g., Craig, 1973, see Allan, 1979). This suggests that performance would differ when prebreak and postbreak intervals are filled or empty. In particular, if they are perceived to be longer when they are filled, intervals should be ended earlier and, consequently, be shorter. This was tested in Experiments 1 and 2.

When prebreak and postbreak intervals were filled in the present study, the breaks were empty, and, conversely, breaks were filled when prebreak and postbreak periods were empty (except for one condition in Experiment 2). A recent study showed that in a standard gap procedure in which the gap or break is empty, rats seem to use a *stop rule*, that is, to time the pregap interval, stop timing during the gap, and resume timing after the gap (Buhusi & Meck, 2000). In a reversed gap procedure in which the gap is filled with a stimulus, a *reset rule* seems to be used instead: Rats respond independent of the duration preceding the gap. The proposed interpretation is that in the reversed condition, a more salient gap filled with a stimulus has attention-attracting properties that are more likely to interfere with the memorized pregap interval, thus resetting timing. If similar effects are observed in the present study, produced intervals should be independent of the prebreak duration when breaks are filled. In that condition, the effect of break location found in previous experiments (Fortin & Massé, 2000) should disappear or be much weaker.

Break duration was manipulated in all experiments. Furthermore, a standard break condition with empty breaks was compared with reversed break conditions with filled breaks in Experiments 1 and 2, between and within experimental sessions, respectively. Experiments 3 and 4 were designed to evaluate the effect of break duration by using a greater number and a wider range of break duration values. In Experiment 5, the hypothesis that preparatory processes take place during the break was tested on a reaction time response provided at the end of the break.

Experiment 1

Two main conditions were contrasted in Experiment 1. In the empty-break condition, there was no stimulus presented during the break, and the prebreak and postbreak periods were filled with an auditory stimulus; this was the filled–empty–filled (FEF) condition. In the filled-break condition, the prebreak and postbreak periods were silent, and a tone was presented during the break; this was the empty–filled–empty (EFE) condition. In both conditions, three break locations (0.7, 1.2, and 1.7 s) and three break durations (1, 2, and 3 s) were used. The target interval to be produced was 2.4 s. All trials included a break.

Method

Participants. Sixteen participants, 9 women and 7 men (mean age = 23.60 years, *SD* = 5.29, range: 19–44), were paid $20 for their participation. They were all naive to the purpose of the experiment. No participant took part in more than one experiment in the present study.

Apparatus and stimuli. A PC-compatible computer running MEL (Micro Experimental Laboratory; Schneider, 1990) software controlled stimulus and feedback presentations. Participants were seated in front of a computer screen, at a distance of about 60 cm from the screen. Temporal intervals were recorded to the nearest millisecond. The participant's preferred hand rested on the numerical keyboard of the computer, and the *0* key was used to produce the time intervals. The experiment took place in a sound-attenuating test chamber, dimly lit with a 40-W bulb.

Procedure. There were two practice sessions, followed by four experimental sessions, two in the empty-break condition, two in the filled-break condition.

A 2.4-s tone was presented five times at the beginning of the first practice session as a demonstration of the target interval to be produced throughout the experiment. There was no mention of its value in time units (e.g., seconds). The participant then practiced producing the target interval in practice sessions. In the first four blocks of these sessions, feedback was provided after each temporal production, informing the participant whether the interval was too short, too long, or correct, within a temporal window of 10% (±120 ms) centered on the target interval. No feedback was given in the last block of practice trials. In practice sessions, each block comprised 48 trials.

There were two successive practice sessions, one in which participants practiced producing filled intervals during which a tone was presented. In these trials, the first keypress triggered a tone presentation, which finished with the end of the interval production. In the other practice session, participants were trained to produce empty intervals with no tone between the two keypresses. The order in which participants were trained in the filled- and empty-interval sessions was counterbalanced.

A practice trial started when the participant began interval production by pressing the *0* key on the numerical keyboard of a computer. In the filled-interval condition, this triggered a tone presentation (550 Hz, 50 dB), which lasted until the interval was ended with a second keypress on the *0* key. When presented, the feedback appeared on the computer screen immediately after the production. The feedback was presented for 1 s and was immediately followed by an asterisk presented at the center of the screen, which remained on until the participant started the following trial.

In experimental trials, the participant began the temporal production when ready by pressing the *0* key. As in practice sessions, a tone presentation coincided with the first keypress in the FEF condition. There was a silent break in tone presentation 0.7, 1.2, or 1.7 s after the first keypress; the break could last for 1, 2, or 3 s. After this duration, tone presentation resumed and lasted until the temporal production was terminated by the participant pressing the *0* key anew. No feedback was presented. An asterisk appeared on the screen immediately after the end of the temporal production and remained on until the participant began the next trial by starting a new interval production. In the EFE condition, the periods preceding and succeeding the break were silent, and the tone was presented during the break period.

In each of the four experimental sessions, there was one 48-trial block of practice with feedback to reset the target duration. The practice block was followed by four 36-trial experimental blocks with breaks, without feedback on temporal performance. There was a 30-s pause between blocks. Sessions lasted approximately 30–40 min. Participants were instructed to execute the interval production as in practice trials, so that the time between the two keypresses, not including the duration of the break period, corresponded to the practiced target duration. Participants were informed that break location and duration would vary from one trial to another.

Location and duration were varied within blocks of trials. A 3 (break location: 0.7, 1.2, and 1.7 s) × 3 (break duration: 1, 2, and 3 s) repeated measures design was used. Values of location and duration were selected randomly in each trial, with the constraint that the number of trials was the same at each combination of factor levels. Each participant completed 32 trials in each of the nine combinations of factor levels, 16 in the FEF condition and 16 in the EFE condition.

The experiment included four experimental sessions, two successive sessions in the FEF condition and two successive sessions in the EFE condition. The order of testing in the two conditions was counterbalanced. Sessions were completed on consecutive days. When two sessions were completed during the same day, they were separated by a minimum delay of 1 hr. No more than two sessions were completed during a single day.

Results

Means and standard deviations of temporal intervals were computed for each participant. Intervals more than three standard deviations from the individual means were discarded, which represented 53 out of 4,608 (1.2%) observations in the FEF condition and 46 out of 4,608 (1.0%) observations in the EFE condition. For each participant, mean produced intervals at each value of break duration and location were computed in the two experimental sessions of the FEF condition and then in the two sessions of the EFE condition. The data submitted to analyses were mean produced intervals not including break duration, that is, defined as the sum of the prebreak and postbreak durations. A repeated measures analysis of variance (ANOVA) was carried out on mean produced intervals, with break location (three levels: 0.7, 1.2, and 1.7 s), break duration (three levels: 1, 2, and 3 s) and stimulus condition (two levels: empty break, filled break) as factors.

Figure 1 shows mean produced intervals, not including break duration, as a function of break location (or prebreak duration), at each value of break duration in the two stimulus conditions. Note that in this task, perfect performance would produce flat functions with an intercept of 2.4 s in all conditions, which means that the sum of prebreak and postbreak durations should correspond to the target interval. The results from the ANOVA showed that productions lengthened with increasing prebreak duration, $F(2, 30) = 15.10, p < .0001$. It can be seen in Figure 1 that productions were longer at the shortest break duration, that is, when break duration was 1 s.

This significant effect of break duration, $F(2, 30) = 22.70, p < .0001$, is shown more specifically in Figure 2, in which mean productions are presented as a function of break duration averaged over the three values of break location; tests for trends revealed that the quadratic trend was significant in this relationship, $F(1, 15) = 10.48, p < .006$. Finally, produced intervals were generally shorter in the FEF condition than in the EFE condition, $F(1, 15) = 11.45, p < .004$.

None of the interactions was significant: interactions between stimulus conditions and break location, $F(2, 30) = 1.45, p = .25$; stimulus conditions and break duration, $F(2, 30) = 1.33, p = .28$; break location and duration, $F(4, 60) = 1.36, p = .26$; and stimulus conditions, break location, and break duration ($F < 1$).

Discussion

The effect of break location found in previous experiments (Fortin & Massé, 2000) was replicated: Productions lengthened with increasing prebreak duration. The effect of break location was not weaker when the break was filled than when it was empty, which suggests that in both conditions, participants used a similar rule for responding, taking into account the prebreak interval in producing the target interval.

A more important result with regard to the main objective of the present study is that productions shortened with increasing break

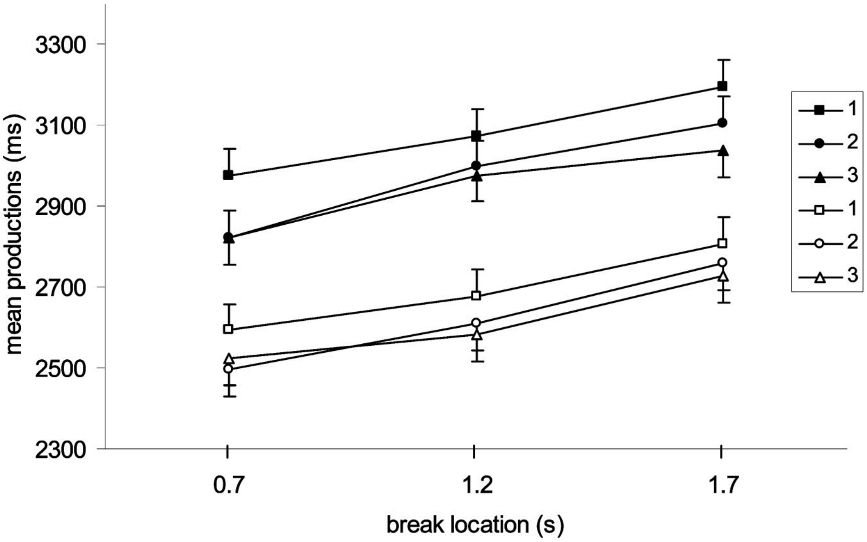

Figure 1. Experiment 1: Mean produced intervals, not including break durations, as a function of break location in the three conditions of break duration (1, 2, and 3 s) and in the filled–empty–filled (black markers) and empty–filled–empty (white markers) conditions. Error bars representing standard errors of the means, computed with a pooled mean square error (see Loftus & Masson, 1994), are shown either above or below the means to reduce overlap of the bars.

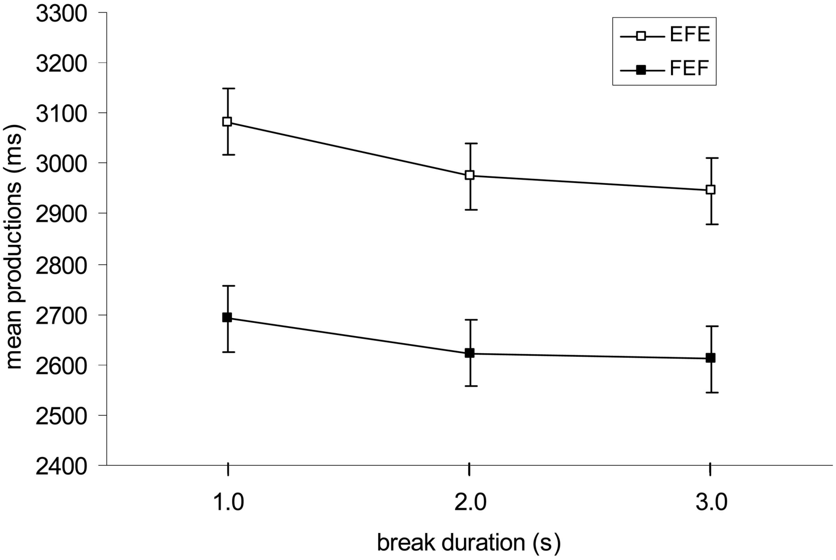

Figure 2. Experiment 1: Mean produced intervals, not including break durations, as a function of break duration in the filled–empty–filled (FEF) and empty–filled–empty (EFE) conditions. Error bars represent standard errors of the means, computed with a pooled mean square error.

duration. This relationship is similar to the relationship between foreperiod and reaction times observed in many studies (e.g., Elliott, 1973; Kellas, Baumeister, & Wilcox, 1969), which supports the main hypothesis that the break would be used as a preparatory period. If during the break, participants prepared to restart timing as soon as the signal ending the break was presented, their level of preparation increased as time elapsed during the break. Increased readiness made participants restart timing more quickly at the end of the break, hence shortening the time necessary to reach the subjective target interval. This would explain why productions shortened as the break lengthened in Experiment 1. The difference in mean productions was greater between 1-s and 2-s breaks than between 2-s and 3-s breaks. As in foreperiod studies (Elliott, 1973; Karlin, 1959; Stilitz, 1972), this nonlinear relationship may be explained by the fact that a peak level of preparation to resume timing is reached around 2 s after the break has started, and that this level may be extended until the end of the longer break duration, 3 s in Experiment 1.

Another notable result was that productions were shorter in the empty-break condition than in the filled-break condition. One factor that could explain this result is the filled-duration illusion (e.g., Craig, 1973). If the ongoing duration was judged longer during a filled interval production, as in the FEF condition, participants should have reached the subjective target duration earlier, thus ending the production earlier. Another factor that may contribute to this result is that a tone onset might be a more efficient signal to resume timing than a tone offset. This would be consistent with data from electrophysiological studies showing that attentional responses to stimulus onset are stronger than those to stimulus offset (see Näätänen, 1992, pp. 120–121). At the end of a break, timing would be resumed more quickly when the signal to resume timing is a stimulus onset than a stimulus offset. Resuming timing more rapidly would contribute to attaining the target duration earlier, and hence result in shorter productions. The filled interval and the stimulus onset as a signal to resume timing could therefore both contribute to obtaining shorter productions in the empty-break condition. However, it was impossible to dissociate these two factors because they were varied conjointly in Experiment 1: When the interval to be timed was filled, the signal to resume timing was always a tone onset.

In reaction time studies, the effect of foreperiod is weaker when the auditory signal is more intense, when stimulus intensity is manipulated within experimental sessions. This was observed whether the foreperiod varied between trials within blocks of trials (Kellas et al., 1969) or between blocks of trials (Niemi, 1979). The proposed interpretation was that a louder stimulus makes participants react quickly, even at shorter foreperiods. If the effect of break duration is a preparatory effect, as suggested by the results in Experiment 1, it should be weaker in the FEF condition than in the EFE condition. This is because in the FEF condition, the signal to restart timing at the end of the break was a tone presentation, which is more intense than a tone interruption as in the EFE condition. There was no interaction between break duration and stimulus conditions in Experiment 1. However, the interaction between foreperiod and stimulus intensity was observed when intensity was manipulated within experimental sessions, not between experimental sessions as in Experiment 1. The interaction was therefore tested in Experiment 2, which was similar to Experiment 1, but in which stimulus conditions were manipulated within experimental sessions.

Experiment 2

The main objectives of Experiment 2 were to replicate the effect of break duration found in Experiment 1 and to verify whether this effect interacts with stimulus condition. Another objective was to distinguish the effect of producing filled or empty intervals from the effect of starting timing on a signal's onset or offset.

As in Experiment 1, there was no stimulus presented during the break in the FEF condition: A tone offset and onset signaled the beginning and the end of the break, respectively. As illustrated in Figure 3, the FEF condition was compared with two conditions in which the break was filled: one in which there was a tone during the whole interval production (prebreak, break, and postbreak periods); this is the filled–filled–filled (FFF) condition. In the other filled-break condition, there was no tone in the prebreak and postbreak periods; this was the empty–filled–empty (EFE) condition. The three stimulus conditions were manipulated between blocks of trials. Therefore, if the break period is used as a preparatory period to resume timing, the effect of break duration may be weaker in the FEF condition than in the EFE and FFF conditions. This is because a tone presentation in the FEF condition is a more intense signal to restart timing than the offset of a visual or auditory stimulus, as in the EFE and FFF conditions.

The three conditions in Experiment 2 also allowed us to compare two conditions in which participants timed a filled interval, but in which timing was resumed on either stimulus onset or offset. If the time to resume timing is shorter on stimulus onset than on stimulus offset, as suggested by the results of Experiment 1, productions should be shorter in the FEF condition than in the FFF conditions, even though the prebreak and postbreak periods were filled with a stimulus in the two conditions. In contrast, if the difference between the FEF and EFE conditions in Experiment 1 was only due to timing filled versus empty intervals, productions should not differ in the FEF and FFF condition in Experiment 2.

Method

The method was similar to that of Experiment 1, with some exceptions described in the following sections.

Participants. Eighteen participants, 10 women and 8 men (mean age = 26.50 years, *SD* = 0.60, range: 20–46), were paid $20 for their participation.

Procedure. As in Experiment 1, participants practiced producing the 2.4-s target duration in practice trials with and without a tone presented during the temporal production. There were two practice sessions, including four 48-trial blocks with feedback on production accuracy and one 48-trial block with no feedback. For half the participants, the first practice session was composed of two blocks of temporal production with a tone presented during the interval, followed by two blocks of silent no-tone trials. The last block comprised 24 trials with tone followed by 24 trials with no tone. The order of tone–no-tone trials was reversed in the second practice session. The other half participants were tested in the same two practice sessions, but in reversed order.

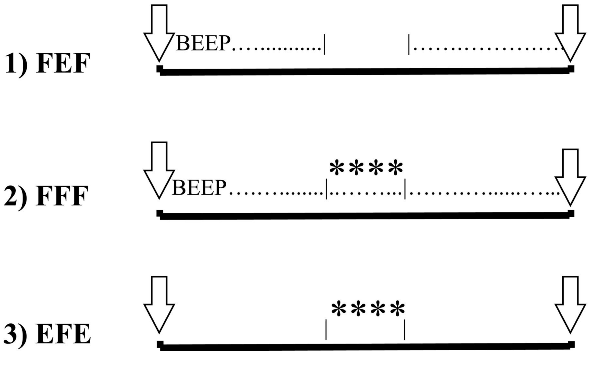

Figure 3. Experiment 2: Conditions of stimulus presentation: (1) Filled–empty–filled (FEF), in which a tone presented during the prebreak and postbreak periods was interrupted during the break period. (2) Filled–filled–filled (FFF) condition, in which a continuous tone was presented between the first and the second keypress and a visual stimulus (asterisks) indicated the break period. (3) Empty–filled–empty (EFE), in which no stimulus was presented during the prebreak and postbreak periods and a visual stimulus was presented during the break.

The three experimental sessions began with a first practice block of production with feedback. This block included 48 trials, 24 with tone followed by 24 with no tone for half the participants, and with the order of tone–no-tone trials reversed for the other half. There were then three 45-trial experimental blocks in either one of the three stimulus conditions illustrated in Figure 3.

In the FEF condition (see Figure 3, top), the first keypress of the temporal production triggered a tone presentation, which was interrupted during the break period and which ended at the end of the temporal production. In the FFF condition (see Figure 3, middle), a visual signal was presented during the break period, and a tone was presented continuously between the first keypress and the second keypress. In these trials, the end of the break period was signaled by the offset of the visual stimulus (a row of asterisks) presented on the center of the screen. In the EFE condition (see Figure 3, bottom), the same visual stimulus was presented during the break, but there was no tone presented between the two keypresses.

Location and duration varied randomly from trial to trial, with the constraint that there were an equal number of trials at each combination of factor levels. As a means of eliminating any possible effects of order in the three stimulus conditions, half participants were tested successively in Conditions FEF, FFF, and EFE in the first experimental session; FFF, EFE, and FEF in the second session; and EFE, FEF, and FFF in the third session. The other half was tested successively in Conditions FFF, FEF, EFE in the first experimental session; EFE, FFF, and FEF in the second session; and FEF, EFE, and FFF in the third session.

Results

Sixty-one outliers (plus or minus 3 standard deviations from the means) were eliminated from the 7,290 collected data. A repeated measures ANOVA was carried out on mean produced intervals not including breaks, defined as the sum of prebreak and postbreak durations, with break duration (three levels: 1, 2, and 3 s), break location (three levels: 0.7, 1.2, and 1.7 s) and stimulus conditions (three levels: FEF, FFF, and EFE) as factors.

The main result in Experiment 2 is that the shortening of produced intervals with increasing break duration was replicated, $F(2, 34) = 21.90$, $p < .0001$, as shown in Figure 4. The function relating productions to break duration was again nonlinear; tests for trends confirmed that the quadratic trend was significant, $F(1, 17) = 15.41$, $p < .001$. Moreover, it can be seen in Figure 4 that the effect of break duration was weaker in the FEF condition than in the FFF and the EFE conditions, an interaction that was significant, $F(4, 68) = 6.33$, $p < .0002$.

There was also a significant effect of stimulus condition, $F(2, 34) = 8.09$, $p < .001$. A posteriori comparisons with Bonferroni adjustment revealed that productions were significantly shorter in the FEF than in the EFE ($p < .01$). The difference between the FEF and the FFF did not reach statistical significance ($p = .08$). Productions did not differ significantly in the EFE and the FFF conditions ($p = .16$).

Finally, the usual effect of break location was observed: Mean productions lengthened with increasing prebreak duration, *F*(2,

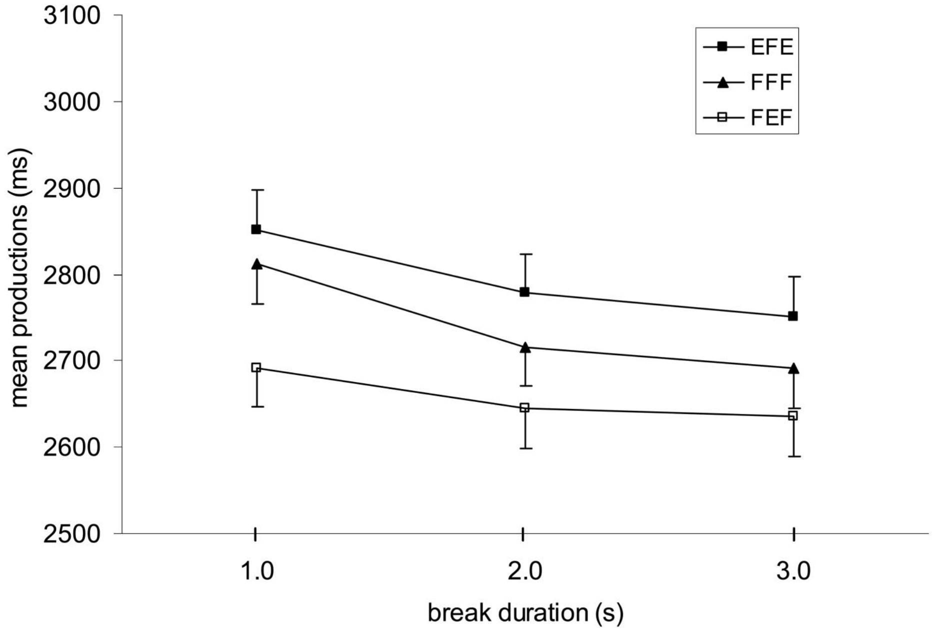

Figure 4. Experiment 2: Mean produced intervals, not including break durations, as a function of break duration in the three conditions of stimulus presentation: filled–empty–filled (FEF), filled–filled–filled (FFF), and empty–filled–empty (EFE). Error bars representing standard errors of the means, computed with a pooled mean square error, are shown either above or below the means to avoid overlap of the bars.

34) = 20.20, $p < .0001$, as shown in Figure 5. None of the other interactions were significant: between break location and stimulus conditions ($F < 1$); break location and break duration, $F(4, 68) = 1.27$, $p = .29$; and break location, duration, and stimulus conditions, $F(8, 136) = 1.35$, $p = .23$.

Discussion

The principal finding in Experiment 2 is that the negative relationship between mean productions and break duration found in Experiment 1 was replicated. This effect was again similar to

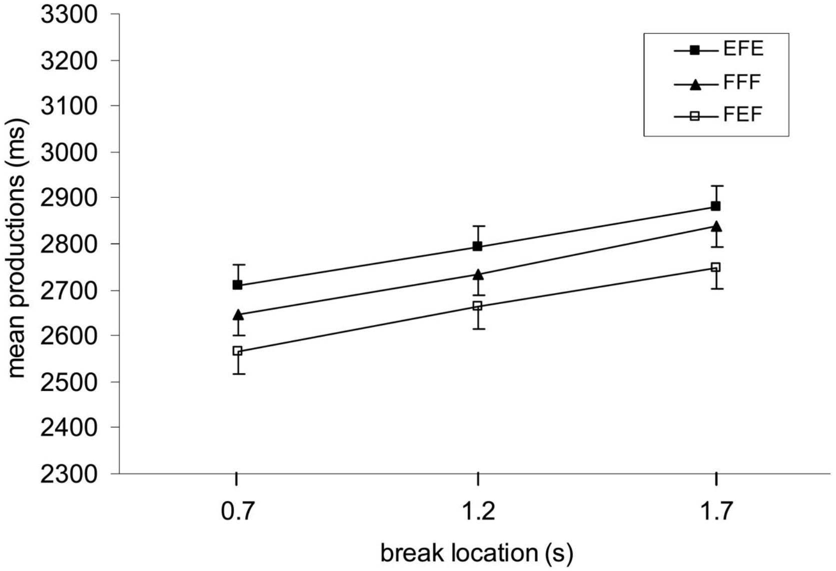

Figure 5. Experiment 2: Mean produced intervals, not including break durations, as a function of break location in the three conditions of stimulus presentation: filled–empty–filled (FEF), filled–filled–filled (FFF), and empty–filled–empty (EFE). Error bars representing standard errors of the means, computed with a pooled mean square error, are shown either above or below the means to avoid overlap of the bars.

that found in foreperiod studies in which the foreperiod varied from trial to trial. As with reaction time, productions shortened with increasing break duration, and the shortening was more pronounced when break duration increased from 1 to 2 s than when it increased from 2 to 3 s. This result supports the hypothesis that the break is used as a preparatory period to resume timing, in a way similar to the preparatory period in reaction time experiments.

Further support for this hypothesis is provided by the interaction showing that this effect was weaker when the signal to restart timing was a tone onset, as in the FEF condition. A similar effect was observed in reaction time studies, in which the foreperiod effect was weaker when the reaction stimulus was more intense (Kellas et al., 1969; Niemi, 1979; Stilitz, 1972). As with reaction time, the interaction between time production and break duration may be explained by the alerting properties of the tone onset in the FEF condition (e.g., Niemi, 1979). The signal to resume timing (i.e., the tone onset), was relatively intense in comparison with the offset of the visual stimulus in the filled-break conditions. A relatively intense signal would compensate for a lower level of preparation at the end of the shortest break duration, so that timing would resume as quickly in this condition as with longer break durations.

Mean intervals differed in the three stimulus conditions in Experiment 2, but the only significant a posteriori comparison was between the FEF and EFE conditions. This suggests that in Experiment 1, the two factors, filled-interval and stimulus onset as a signal to resume timing, both contributed to the fact that productions were shorter in the FEF condition than in the EFE condition.

Experiment 3

The results obtained so far indicate that productions were longest at the shortest break duration and shortened nonlinearly with break duration. Only three values of break duration, 1, 2 and 3 s, were used in Experiments 1 and 2 however, which is the minimum number of values to detect a nonlinear relationship. The objective of Experiment 3 was to verify the nonlinear relationship with a greater number of break duration values and to evaluate the generality of the effect with a wider range of break durations. Six break duration values varying between 0.8 and 5.8 s were therefore used in Experiment 3 in a standard break condition, that is, in an FEF condition.

Method

Participants. Twenty participants, 13 women and 7 men (mean age = 22.4 years, *SD* = 6.39, range: 16–48), were paid $20 for their participation.

Procedure. The experiment comprised two practice sessions and three experimental sessions. A target duration slightly different from that used in Experiment 1 and 2, 2.1 s rather than 2.4 s, was used in Experiment 3 to enhance the generality of results. Participants were therefore trained to produce the 2.1-s target interval in two practice sessions including four 48-trial blocks with feedback on production accuracy and one 48-trial block with no feedback. In all practice trials, there was a tone (550 Hz, 50 dB) presented between the first and second keypresses during the temporal production. In experimental trials, the same tone started and ended on the first and second keypresses bounding the temporal production, but was interrupted during the break period. Each of the three experimental sessions comprised one 48-trial practice block followed by four blocks including 48 experimental trials of time production with breaks. Location and duration varied randomly from trial to trial, with each combination of factor levels comprising an equal number of trials.

Results

One hundred and fifteen outliers (plus or minus 3 standard deviations from the means) were eliminated from the 11,520 collected data. A repeated measures ANOVA was carried out to test the effect of break duration (six levels: 0.8, 1.8, 2.8, 3.8, 4.8, and 5.8 s) and of break location (two levels: 0.7 and 1.7 s) on mean produced intervals not including breaks.

Mean produced intervals shortened with increasing break duration, $F(5, 95) = 8.75$, $p < .0001$, as shown in Figure 6. A trend analysis revealed that the quadratic trend was significant, $F(1, 19) = 6.07$, $p = .02$. Tests for higher trends were nonsignificant. Productions were also longer when the break occurred 1.7 s after the start of the temporal production ($M = 2{,}642$, $SD = 357$) than when it occurred at 0.7 s ($M = 2{,}417$, $SD = 277$), $F(1, 19) = 23.81$, $p < .0001$. The interaction between location and duration was not significant, $F(5, 95) = 1.61$, $p < .17$.

Discussion

The critical finding in Experiment 3 was that with a greater number of break values, the function relating time productions and break duration was again negative and nonlinear, as in foreperiod studies in which equally probable foreperiods vary from trial to trial (e.g., Drazin, 1961; Karlin, 1959; Kellas et al., 1969). As in Experiment 1 and 2, these results may be explained by increased readiness to restart timing when the signal ending the break occurs later because of increased conditional probability of signal occurrence as time elapses during the break (e.g., Requin & Granjon, 1969; Stilitz, 1972). The relationship was clearly nonlinear: Productions shortened with increasing break duration from 0.8 to 3.8 s, but increasing the break duration beyond 3.8 s had no effect. This may be explained by the fact that readiness was at its highest level around 3.8 s and that this level could be maintained up to 5.8 s.

Experiment 4

The functions relating mean productions to break duration were similar whether the break values covered a 1–3-s range (Experiments 1 and 2) or a 0.8–5.8-s range (Experiment 3). However, this comparison was made between experiments in which two different target intervals to be produced were used: 2.4 s in Experiments 1 and 2, and 2.1 s in Experiment 3. Experiment 4 was designed to compare, in a within-subject design, the similarity of the functions relating productions to break duration when the same target interval and three or six values of break durations are used, but with the same range of duration values and the same average duration value.

The six-break-duration condition in Experiment 4 also allowed us to test, under new conditions, the main finding of Experiment 3, which was that productions shorten and then stabilize when break duration varies between 0.8 and 5.8 s.

Method

Participants. Fourteen participants, 9 women and 5 men (mean age = 22.8 years, *SD* = 4.21, range: 18–35), were paid $20 for their participation.

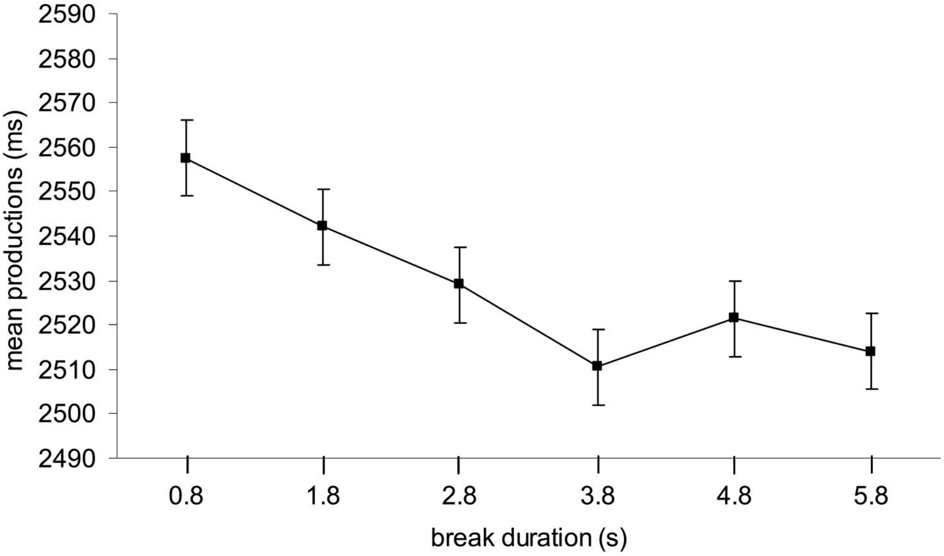

Figure 6. Experiment 3: Mean produced intervals, not including break durations, as a function of break duration. Error bars represent standard errors of the means, computed with a pooled mean square error.

Procedure. The procedure was identical to that of Experiment 3, with the following exceptions: Participants completed three practice sessions, in which they were trained to produce the 2.1-s target interval. They then completed one experimental session in one of the two break-duration conditions (three or six break durations), one practice session, and one experimental session in the other break-duration condition. In each of the two experimental sessions, there was a first block of practice trials of time interval production with no breaks. This block included 24 trials with feedback on time production accuracy, followed by 24 trials with no feedback.

Participants were tested in two experimental sessions, one using three values of break duration, and one using six values. The order in which participants were tested in the two types of experimental sessions was counterbalanced. The number of possible values of break duration, three or six, was not mentioned explicitly to the participants. Instead, they were familiarized with the experimental condition through a block of 48 practice trials with breaks, but with no feedback on time production accuracy. This block of practice trials with breaks was followed by four 48-trial blocks with either three or six possible values of break duration, depending on the experimental session. The data from the four 48-trial blocks were used in data analyses. Within each experimental session, the break duration values were equally probable, and the average break duration was 3.3 s.

Results

Overall, 2,688 observations were collected, and 32 outliers (plus or minus 3 standard deviations from the means) were eliminated for data analysis in the six-duration conditions. In the three-duration condition, 2,688 observations were also collected, and 28 outliers were eliminated. Two ANOVAs were performed on data from the two experimental designs used in the experiment, the 2 (break location: 0.7 and 1.7 s) × 3 (break duration: 0.8, 3.3, and 5.8 s) and the 2 (break location: 0.7 and 1.7 s) × 6 (break duration: 0.8, 1.8, 2.8, 3.8, 4.8, and 5.8 s) repeated measures designs, with mean produced intervals, not including breaks, as the dependent variable.

Figures 7A and 7B show mean produced intervals as a function of break duration when three and six duration values were used. In the experimental session using six values of break duration, there was a significant effect of break duration, $F(5, 65) = 2.47$, $p < .05$. Productions decreased nonlinearly with increasing break duration, a trend supported by a marginally significant quadratic component, $F(1, 13) = 4.32$, $p = .058$. Mean productions were shorter when the break signal was presented 0.7 s after the beginning of temporal production than when it was presented at 1.7 s (0.7 s: $M = 2{,}583$ ms, $SD = 469$; and 1.7 s: $M = 2{,}901$ ms, $SD = 591$), $F(1, 13) = 16.03$, $p < .002$. The interaction between location and duration was not significant, $F(5, 65) = 1.58$, $p = .18$.

When there were three values of break duration, productions also varied with break duration, $F(2, 26) = 5.90$, $p < .008$. The quadratic trend in the function relating productions to the three values of break duration was significant, $F(1, 13) = 4.80$, $p < .05$. Mean productions were again shorter when prebreak duration was 0.7 s than when it was 1.7 s (0.7 s: $M = 2{,}585$ ms, $SD = 442$; and 1.7 s: $M = 2{,}903$ ms, $SD = 590$), $F(1, 13) = 16.13$, $p < .001$. The interaction between location and duration was not significant ($F < 1$). Finally, mean produced intervals did not differ significantly whether there were three or six values of break duration (3 durations: $M = 2{,}742$ ms, $SD = 409$; and 6 durations: $M = 2{,}741$ ms, $SD = 434$; $F < 1$).

Discussion

As in Experiment 3, the functions relating productions to break duration were very similar, whether three or six duration values were used, when the average and the range of break durations was identical. Furthermore, when six break values between 0.8 and 5.8 s were used, as in Experiment 4, productions shortened and then became stable around a break value of 3.0 s. This suggests that a peak level of readiness to restart timing was reached 3.0 s after the beginning of the break, a peak level that could be maintained for 2.8 s longer, that is, until the end of the break.

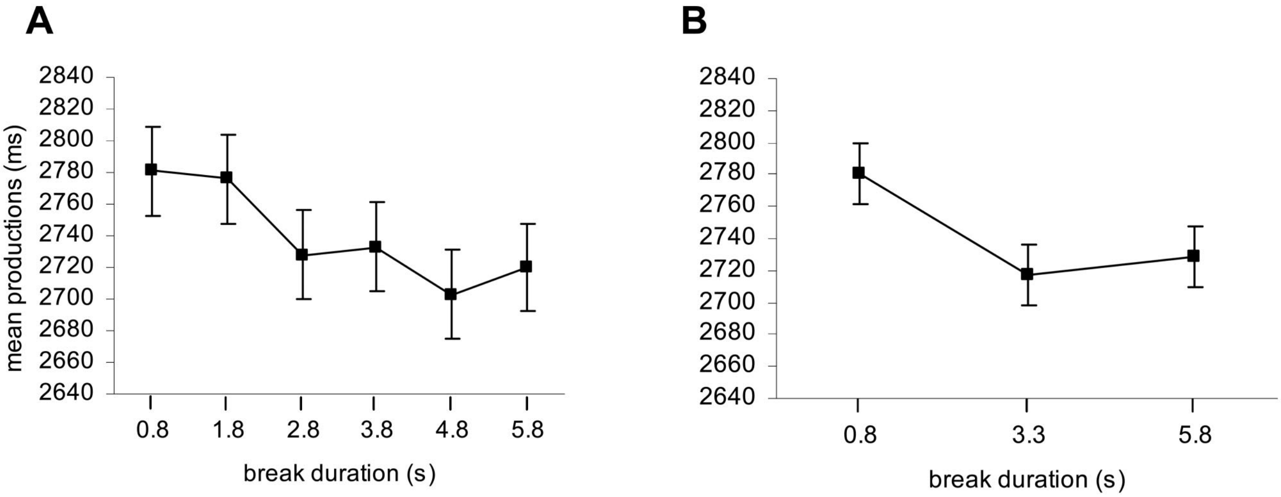

Figure 7. Experiment 4: Mean produced intervals, not including break durations, as a function of break duration, when six (A) and three (B) break duration values are used. Error bars represent standard errors of the means, computed with a pooled mean square error.

Experiment 5

Many aspects of the data in Experiments 1–4 support the hypothesis that, in a way similar to a foreperiod, a break in time production is used as a preparatory period to react to the stimulus indicating that timing be resumed at the end of the break. Experiment 5 was designed to test this hypothesis more directly by asking participants to provide a reaction time response to the signal ending the break, in addition to the usual time production response. We predicted that reaction time would be negatively related to break duration because the break is used as a preparatory period to react to the signal's presentation.

Method

Participants. Ten participants, 2 women and 8 men (mean age = 35.10 years, *SD* = 10.42, range: 21–48), were paid $20 for their participation.

Procedure. The procedure was identical to that of Experiment 3 and to that of Experiment 4 in the three-break-duration condition, with the following exceptions: Participants completed two practice sessions in which they were trained to produce the 2.5-s target interval. A longer target interval was used in Experiment 5 than in Experiments 3 and 4 (which used a 2.1-s interval) to give participants enough time to execute the two responses during the postbreak period. The participants then completed three experimental sessions in which they produced the target interval by pressing the *0* key of the numerical keyboard twice with their right hand. The first keypress starting the interval production triggered a tone presentation that ended with the second keypress ending the interval production. During the interval, the tone was interrupted and then resumed, which delimited the break period. Participants were asked to press the spacebar of the computer keyboard with their left hand as quickly as possible when the tone resumed, which was the signal ending the break period. The break could last 0.8, 3.3, or 5.8 s.

Two responses were recorded: time interval production and the time to react to the signal (tone) presentation ending the break. The time interval production was defined, as in the previous experiments, as the time elapsing between the two *0* keypresses, from which the break duration was subtracted. Reaction time was defined as the time between the beginning of the tone presented at the end of the break and the time when the space bar was pressed.

In each of the three experimental sessions, three equally probable values of break duration were used and were varied from trial to trial. Break location and duration were varied in a repeated measures design.

Results

Overall, 4,320 reaction times and 4,320 produced time intervals were collected. From the reaction time data set, 69 outliers (plus or minus 3 standard deviations from the means) were eliminated, which represented 1.6% of the total number of reaction times that were collected, and 46 (1.07%) were eliminated from the time production data set for the same reason. Two separate ANOVAs were carried out, one on mean produced intervals not including breaks and one on reaction times, both with break location (two levels: 0.7 and 1.7 s) and break duration (three levels: 0.5, 3.3, and 5.8 s) as factors.

Figure 8A shows mean reaction times as a function of break duration. Reaction times decreased significantly with increasing break duration, $F(2, 18) = 5.48$, $p = .01$. The quadratic component of this negative relationship was significant, $F(1, 9) = 7.56$, $p = .02$. Reaction times did not differ with break location, $F(1, 9) = 3.85$, $p > .05$. There was no interaction between break duration and location ($F < 1$).

Mean produced intervals are shown as a function of break duration in Figure 8B. Productions did not vary with break duration ($F < 1$), but varied with break location, that is, lengthened with increasing prebreak duration, $F(1, 9) = 20.78$, $p < .001$. The interaction between break duration and location was not significant, $F(2, 18) = 1.07$, $p > .05$.

Discussion

The key finding in Experiment 5 was that the reaction time to the onset of the stimulus to be timed after the break decreased with

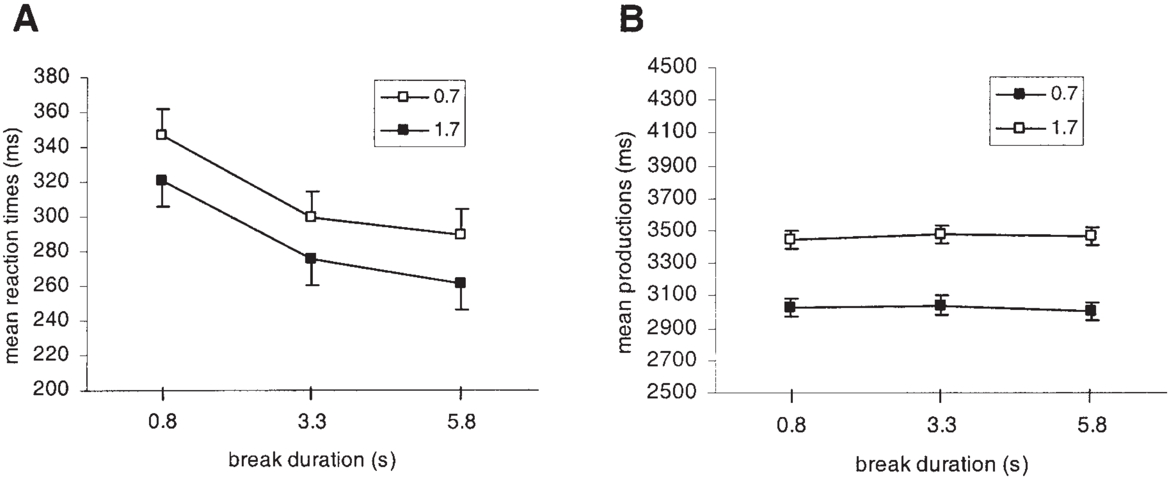

Figure 8. Experiment 5: A: Mean reaction times as a function of break duration at each value of break location. B: Mean produced intervals, not including break durations, as a function of break duration at each value of break location. Legends indicate break locations. Error bars representing standard errors of the means, computed with a pooled mean square error, are shown either above or below the means to avoid overlap of the bars.

increasing break duration. The reaction time–break duration function is very similar to the function relating time production and break duration in the four previous experiments of the present study, that is, is negative and nonlinear. This supports the parallel proposed in the previous experiments between reaction time in foreperiod studies and the latency to restart timing in time production with breaks.

It seems that participants could not increase their level of alertness simultaneously for two responses. In effect, two responses were required at the end of the break in Experiment 5, pressing a key (the reaction time response) and restarting timing. Reaction times decreased with increasing break duration, but time productions did not vary. This suggests that participants could not use the temporal information provided by the break in preparation to the reaction time and production responses concurrently.

Produced intervals were somewhat longer in Experiment 5 than in the previous experiments of the present study, mainly because a longer target interval was used, but also possibly because a motor response had to be provided in the postbreak period in Experiment 5, but not in the previous experiments.

General Discussion

In the present study, a clear and stable, negative, nonlinear relationship between time productions and break duration was found in various experimental conditions. This was interpreted as suggesting that during the break, participants use the temporal information as a preparatory period to restart timing as quickly as possible at the end of the break, in a way similar to the foreperiod in reaction time studies. This hypothesis was tested directly in Experiment 5, in which a reaction time response was required in addition to the time production response. The usual effect of preparatory period was observed on reactions times, confirming the interpretation proposed to explain production data.

The form of the function relating productions to break duration is remarkably similar to that of functions relating reaction time to foreperiods in many studies (e.g., Drazin, 1961; Elliott, 1973; Requin et al., 1973; Stilitz, 1972; for a review, see Niemi & Näätänen, 1981). Although the exact relationship between reaction time and foreperiod is known to be influenced by many variables, this function is usually negative when the preparatory period varies from trial to trial, which is explained by increasing expectancy of the signal's arrival as time elapses during the preparatory period. This expectancy would be related to the conditional probability of the signal's arrival, which increases with the passage of time after the warning signal (Requin & Granjon, 1969; Stilitz, 1972). As in foreperiod experiments, the relationship is nonlinear: Productions shorten, then tend to stabilize. This suggests that as in foreperiod studies (Karlin, 1959), readiness to resume timing would reach a peak at some point during the break and could be maintained for some time.

Another result tends to support the interpretation of the effect of break duration in terms of preparation. Although break duration affected productions in all conditions, the effect was weaker in Experiment 2, when the signal to resume timing at the end of the break was relatively intense in comparison with other conditions used in the same experimental session. Similarly, the effect of preparatory period was shown to be weaker when the reaction stimulus was relatively intense (Kellas et al., 1969; Stilitz, 1972).

In reaction time experiments in which the frequency distribution of foreperiods is rectangular and varies within a group of trials, the passage of time after the warning signal transmits some information to the subject: As time elapses, the signal's arrival becomes more probable, given that it has not already occurred (Requin & Granjon, 1969). The break period in time production would correspond to the foreperiod in reaction time studies, with the break onset and the break offset acting as the warning and reaction stimuli, respectively. At the end of the break, timing must be resumed quickly in order to produce the target interval as precisely as possible. When the break duration is shorter, participants may be relatively unprepared to resume timing at the end of the break, which results in a longer delay to resume timing. This delay in accumulation would postpone the time when the subjective target interval is reached, which results in longer produced intervals. This interpretation is illustrated in Figure 9.

The interval production is started with the first keypress (Kp-1 in Figure 9). In a trial with no break, in which no break is expected (light gray line), accumulation of temporal information (pulses) proceeds with no interruptions until a criterion amount of temporal information corresponding to the target interval is reached (*a* in Figure 9). Reaching the criterion triggers the end of the temporal production with a second keypress (Kp-2a, light gray line and arrow in Figure 9). When an interruption in timing is expected, the accumulation process also starts on the first keypress, but attentional shifts from accumulation to monitor the source of the break signal induce microinterruptions in accumulation. This slows down the accumulation process until the break signal is presented, that is, the break onset. The period of relative loss in accumulation caused by attentional time-sharing is represented with the dotted line between Kp-1 and break onset in Figure 9 (circled with the larger ellipse).

In series of trials with breaks, as in the experiments of the present study, participants know that they will have to resume accumulation at the end of the break. They would therefore use the break period, during which timing is interrupted, as a period of attentional preparation to resume timing at the end of the break. Assuming some latency to start and stop timing (closing and opening of the switch in a temporal information-processing model; see Gibbon et al., 1984), the latency to resume accumulation is longer at shorter break durations because, in these trials, participants are less prepared to resume timing at the end of the break. The period of relative loss in accumulation caused by a lower state of attentional preparation to resume timing is circled with the small ellipse in Figure 9. When accumulation is resumed after the break, it proceeds until the criterion is reached (*b* in Figure 9), which triggers the end of production with the second keypress (Kp-2b in Figure 9).

The effect of break location, which was the main manipulation of interest in Fortin and Massé's (2000) study, was consistently significant in that study as well as in the present one. Finally, whereas the effect of break location was replicated in a time discrimination paradigm, there was no significant effect of break duration in those experiments (Tremblay & Fortin, 2003). This suggests that interval production might constitute a more sensitive measure than a binary classification response in a time discrimination paradigm.

Two distinct attentional factors therefore explain effects of break location and duration in time production with breaks: attentional time-sharing and readiness to resume timing resulting from preparatory processes during the break. Time-sharing takes place before the break and reduces the amount of temporal information

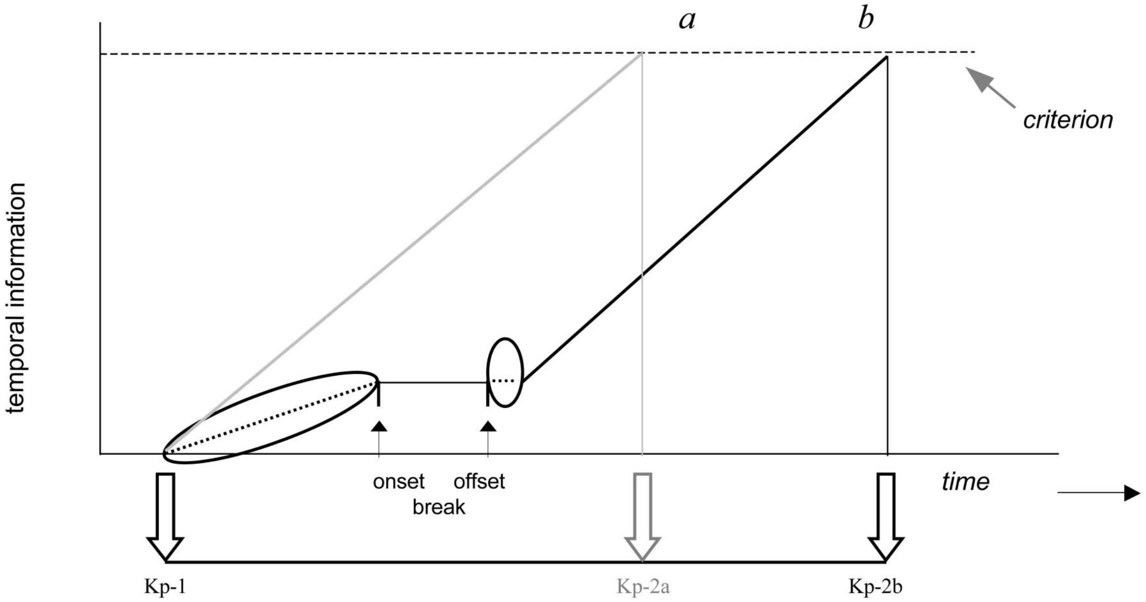

Figure 9. Accumulation of temporal information during an interval production. In a trial with no break, when no break was expected (shown in light gray), accumulation would start on the first keypress (Kp-1) and continue until a criterion amount of temporal information corresponding to the target interval to be produced was reached (*a*). This would trigger the end of temporal production with a second keypress (Kp-2a). In trials with a break that was expected, accumulation would start on Kp-1 also but would be slower before the break because of attentional shifts from accumulation to monitor the source of the break signal. Accumulation would be interrupted during the break itself, at the end of which accumulation would resume with some latency. This latency would be longer at shortest break durations, when participants were less prepared to resume timing. Relative loss in accumulation caused by attentional factors occurred twice (a) before the break, because of attentional time-sharing taking place before its occurrence, and (b) immediately after the break, because of longer latency to resume timing with lesser attentional preparation. Once resumed, accumulation proceeded until the criterion was reached (*b*), triggering the end of production (Kp-2b).

accumulated before the break; preparatory processes take place during the break. If the level of preparation achieved at the end of the break is lower, this would cause some relative loss of temporal information when the accumulation process is resumed at the end of the break. Both factors would influence the operation of a mechanism such as a switch that controls accumulation of temporal information. Before the break, attentional shifts would induce microinterruptions in accumulation. Within this interpretation, accumulation proceeds, before the break, according to an on–off operation mode that depends or whether time is selected as the focus of attention. This is similar to the action of a "flickering switch," as discussed in recent articles on the role of selective attention in timing (Lejeune, 1998, 2000; Zakay, 2000). The effect of break duration is explained by an increased latency to close the switch, thus allowing pulse accumulation (Meck, 1984). Latency to close the switch would be relatively long when break duration is short because readiness to resume timing is lower.

In Fortin and Massé as well as in the present study, produced intervals were generally longer, in trials with breaks, than the target durations to be produced. This might be explained by some general loss of temporal information when timing is interrupted and then resumed, if resuming timing takes more time than interrupting timing. In effect, assuming that stopping timing is not immediate when the break signal occurs, some temporal information would be accumulated at the beginning of the break period. Similarly, assuming that some time is needed to resume timing even at the longest break durations, some temporal information would be lost at this point. If resuming timing is longer than stopping timing, as suggested in some animal studies (see Church, 1997), the net effect would be a loss in accumulation resulting in longer productions, independently of the break duration or location.

In Experiment 5, the effect of break duration on produced intervals was eliminated when participants had to provide a reaction time response at the end of the break in addition to restarting timing. This suggests that participants could not use the preparatory processes in parallel for both timing and reaction time tasks. Although this observation was made in a timing and reaction time dual-task condition, it would be interesting to study concurrency of preparatory processes in a standard foreperiod paradigm, with two simultaneous reaction times tasks, and to see whether similar results would be obtained in these conditions.

A noteworthy contribution of the present study is that it demonstrates common patterns of performance in timing and reaction time, two separate lines of research presenting fundamental points of convergence (Grosjean, Rosenbaum, & Elsinger, 2001). In reaction time studies, participants seem to use the foreperiod to anticipate the onset of the reaction stimulus, which would be based on the ability to time the foreperiod's duration (Kornblum, 1973; Ollman & Billington, 1972; see also Grosjean et al., 2001). Our study suggests that as with reaction time, time-related anticipation plays a significant role in components of timing tasks other than the duration explicitly required to be timed. Future experiments, in which the numerous factors influencing foreperiod effects would be tested in the context of timing experiments, should help in understanding the role of preparatory periods and anticipation in timing.

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