Judgments of the duration of visually marked empty time intervals: Linking perceived duration and sensitivity

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The capability of subjects to categorize (as short or long) visually marked empty time intervals was investigated in three experiments. Two visual signals, located 18° to the left (L) and to the right (R) of a fixation point in the visual field, established four marking conditions, two unilaterally presented (L-L and R-R) and two bilaterally presented (L-R and R-L). In Experiments 1 and 2, the results show that discrimination is better with unilateral sequences than with bilateral sequences and that the perceived duration is longer with an L-R than with an R-L sequence. In addition, Experiment 2 shows that, in comparison with a condition in which Markers 1 and 2 remain identical for a complete session, varying the markers from trial to trial does not decrease discrimination. Also, Experiment 2 shows that discrimination is better when both visual markers are presented at fovea than it is in the unilateral conditions. Experiment 3 shows that bilateral intervals are perceived as being longer and are better discriminated than are intervals marked by an intermodal sequence (auditory-visual or visual-auditory). The general discussion reports the implications of having different perceived duration and sensitivity levels, in various marker-type conditions, for an internal-clock hypothesis. Some implications of these results for a lateralized-timer hypothesis are also discussed.

In the experiments reported in this article, subjects were asked to categorize time intervals as being short or long (a task referred to below as duration discrimination). These intervals are marked by two brief visual signals presented to the left (L) or to the right (R) visual field. This determines four marker-type conditions, two being unilateral (L-L or R-R sequences: Experiments 1 and 2) and the other two being bilateral (L-R or R-L sequences: Experiments 1 to 3).

The empirical work reported in the present article is in the tradition of time psychophysics where duration discrimination is a task frequently employed (for excellent reviews, see Allan, 1979; Allan & Kristofferson, 1974; or Killeen & Weiss, 1987). With a psychophysical approach to psychological time, judgments on duration are said to rely on an internal clock. To determine how this clock works, it is essential to know what nontemporal factors influence time judgments. For duration discrimination, one such factor is the method used to mark intervals. In most

empirical studies on the mechanisms underlying duration discrimination, time intervals have been marked by auditory stimuli (Creelman, 1962; Divenyi & Danner, 1977). Some studies on this issue have used visual signals (see Allan & Kristofferson, 1974). In the latter research, the effect of signal characteristics was under investigation (Allan, Kristofferson, & Wiens, 1971; Fetterman & Killeen, 1992; Nilsson, 1969). However, these signals were generally presented at the fovea area (Oostenbrug, Horst, & Kuiper, 1978), and not much is known about the effect of signal location in the visual field. The experiments reported below explored the effects on duration discrimination of a variety of experimental conditions in the visual mode.

In the time psychophysics literature, errors in duration-discrimination tasks are mainly attributed to the properties of an internal clock. This clock is described as a pacemaker-counter device. The pacemaker emits pulses, and the accumulation of these pulses is the basis for the perceived duration of an interval—more pulses result in a longer perceived duration. In this model, sensitivity depends on the variability, from trial to trial, in the number of pulses accumulated. The variability is expected to increase with longer intervals, that is, as a function of the mean number of pulses. More specifically, this variability is expected to depend mostly on the emission properties of the pacemaker (Allan & Kristofferson, 1974; Creelman, 1962; Getty, 1975; Killeen & Weiss, 1987), as well as on such nontemporal factors as attention (Grondin & Macar, 1992; Macar, Grondin, & Casini, 1994; Meck, 1984) and the latencies between physical signals marking an interval and the internal onset and

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offset of the timing period (Allan et al., 1971; Grondin, 1993).

In the internal-clock model, the variability in the number of pulses accumulated should increase as a function of this accumulation. Where there are reasons to expect a larger accumulation of pulses, we should also expect larger variability, that is, lower sensitivity. Indeed, there are reasons to think that this accumulation might change with different marker-type conditions. The aim of the present study was to verify when, with visual signals, these accumulation changes occur and to verify whether or not sensitivity is related to these changes.

Using unilateral or bilateral sequences might affect the perceived duration of a given interval. The occurrence of Marker 1 should attract attention in the direction of the signal, either left or right. If Marker 2 is delivered at the other location, then there might be a delay in detecting the signal, which should result in a delay of the internal moment indicating a stop to the timing activity, that is, the pulses' accumulation period. Consequently, the bilateral sequences might be perceived as being longer than the unilateral sequences. Also, such a longer accumulation for bilateral sequences might result in more variability. Thus, this would predict better discrimination for unilateral intervals than for bilateral sequences.

Furthermore, there might also be some difference between the two bilateral sequences with regard to the perceived duration. Sekuler, Tynan, and Levinson (1973) reported that when two brief visual signals are presented in a rapid sequence, one to the left and one to the right, the former is reported to occur first. Indeed, Sekuler et al. estimated that the interval between two signals presented in an R-L sequence should be about 10 msec greater than the interval in an L-R sequence to make these sequences appear to be of equal length. This finding was reported to depend on the property of an internal mechanism that would scan visual inputs in a left-right order (see also Bryden & Mondor, 1991, or White, 1969). Applying this scanning mechanism to the context of duration discrimination of a visually marked interval leads to the following prediction: an L-R sequence defines a longer time period than does an R-L sequence. Also, consequently, sensitivity might be higher with an R-L sequence than with an L-R sequence if the former provided a shorter period of pulse accumulation.

These predictions were tested in two experiments. In Experiment 1, the experimental conditions were restricted to a context of uncertainty, that is, where the origin—to the left or right visual field—of both Marker 1 and Marker 2 is unknown in each trial. Assuming that only one response criterion is adopted for all marker-type conditions, this uncertainty would allow us to compare directly the perceived duration of the bilateral versus the unilateral sequences and of the L-R versus the R-L sequences. In Experiment 1, the method of constant stimuli was employed.

The specific consequences of this uncertainty on sensitivity is unknown. In Experiment 2, subjects were tested

both in the uncertainty condition and in a certainty condition, that is, where the signal used for both markers remained the same for a complete session. In addition to providing an opportunity to replicate the findings of Experiment 1, the second experiment also tested the effect on the overall sensitivity of the randomization from trial to trial of different marker-type conditions. Moreover, an additional control was inserted in the design of Experiment 2 in order to compare unilateral sensitivities with sensitivities when both markers were presented at fovea. In Experiment 2, given that the number of experimental conditions was increased, a method requiring fewer trials was selected to estimate perceived durations and sensitivities.

Finally, a third experiment provided a comparison, for perceived duration and sensitivity, of intervals marked bilaterally with intervals marked by an intermodal sequence, either auditory-visual or visual-auditory.

EXPERIMENT 1

This experiment was designed to provide a first test of the predictions reported above. L-L, L-R, R-L, and R-R sequences were randomly presented. This permitted different comparisons of the perceived durations of unilateral versus bilateral sequences and of the L-R versus R-L sequences.

Method

Subjects. Eight 18- to 23-year-old volunteer students at Laurentian University participated in this experiment. They were paid \$27 (Canadian) for their participation. All subjects reported being right-handed when asked with what hand they performed unimanual tasks; only one reported being a nonconsistent right-hander (Gilbert & Wisocki, 1992; Peters & Murphy, 1992).

Apparatus and Stimuli. Each observer was seated in a chair in a dimly lit room and asked to respond either "short" or "long" by pressing the left or right button, respectively. Adjacent to each button on the response box was a small light that provided feedback, a 1.7-sec signal, after each trial. The left and the right light indicated that the intervals were short or long, respectively. The experiment was controlled by an IBM microcomputer.

Each empty interval was marked by two successive 20-msec visual stimulations. The visual signals consisted of two identical circular red LEDs (Radio Shack No. 276-088). They were located at about 1 m from the eyes of the subjects, subtending a visual angle of about .57°. Those LEDs were located, respectively, 18° to the left (L) and 18° to the right (R) of a fixation point placed in front of the subject. This fixation point was another LED, which are kept unlit. The factorial combination of these two locations resulted in four marker-type conditions: L-L, L-R, R-L, R-R.

Procedure. Each trial consisted of the presentation of a single interval (many-to-few procedure). The subject was asked to judge the time interval from the offset of the first signal to the onset of the second signal, to not move the eyes, and to respond by pressing the appropriate button. The lengths of this interval were 200, 220, and 240 msec (short category), and 260, 280, and 300 msec (long category). The feedback signal was presented 200 msec after the response and was followed by a 1-sec intertrial interval. The visual feedback indicated if the presented interval belonged to the short or the long category.

There were six sessions in the experiment, with six blocks of 72 trials per session. Within each block, there were three repetitions of each of the 24 conditions: 4 marker types $\times$ 6 time intervals. Each

point of each psychometric function was estimated on the basis of 108 trials.

The long distance between the markers, in addition to the requirement that the eyes not be moved, made reasonable the assumption that the signals delivered to the left and to the right of the subject were received in the right and left hemispheres, respectively. Moreover, the 20-msec markers were too brief to allow the subject to move his/her eyes to fixate them given that the latency of eye movement is typically about 180 to 250 msec (Alpern, 1971; Saslow, 1967).

Dependent variables. For each subject and for each marker condition, a 6-point psychometric function was traced, plotting the six comparison durations (from short to long) on the *x*-axis and the probability of responding "long" on the *y*-axis. The cumulative normal distribution (CND) was fitted to the resulting curves. Two dependent variables were extracted from each function, one for sensitivity and one for the perceived duration.

Sensitivity was measured with the estimate of one standard deviation (*SD*) on the psychometric function: the difference between the *x* values corresponding to 84% and 16% of long responses, on the *y*-axis, was divided by 2. Using 1 *SD* (or variance) is a common way to express sensitivity (Killeen & Weiss, 1987), which allows us, for instance, to compare predictions of different clock models for duration discrimination (Getty, 1975; Grondin, 1996) or to compare performances for interval discrimination and production (Ivry & Hazeltine, 1995).

The other dependent variable was the adaptation level (*AL*; see Helson, 1964), that is, the *x* value corresponding to 50% of long responses on the *y*-axis. The shift of the *AL* for the different experimental conditions is interpreted here as an indication of differences in perceived duration. What is assumed is that, with the uncertainty conditions of the present experiment, the subject works with one response criterion for all conditions and that differences in the distribution of short and long responses depend on the speed of signals to start and to stop the internal timekeeping activity.

Results

Two dependent variables are of interest: the *AL*, which provides an estimate of the perceived duration, and the *SD*, which is the estimate of sensitivity (discriminability).

Figure 1 reports the mean *AL* for each experimental condition. Overall, the *AL* is about 261 msec, which indicates that subjects tended to respond "short" slightly

more often than "long." The *AL* is positive (i.e., above 250 msec) in three conditions, L-L (259 msec), R-R (269 msec), and R-L (285 msec), but negative in the L-R condition (232 msec). Indeed, all subjects have a higher *AL* in the R-L condition than in the L-R condition.

The difference between the mean *AL* of each condition was tested with a within-subjects factorial analysis of variance (ANOVA): 2 Marker 1 (L or R) $\times$ 2 Marker 2 (L or R). The results showed a significant difference between L and R for the Marker 1 effect [$F(1,7) = 17.22, p < .01$] and for the Marker 2 effect [$F(1,7) = 17.54, p < .01$]. The interaction was not significant. Thus, there were more "long" responses when Marker 1 was delivered to the left than when it was delivered to the right visual field, and more "long" responses when Marker 2 was delivered to the right than when it was delivered to the left visual field. Moreover, a direct comparison of the L-R and R-L sequences revealed that the *AL* was significantly higher in the R-L condition [$t(7) = 5.30, p < .01$].

Regarding the results for the standard deviation, two observations are noteworthy (Figure 2). First, unilateral sequences are clearly better discriminated than bilateral sequences. Second, the R-L or L-R sequences lead to about the same discrimination level.

The difference between the mean standard deviation of each condition was tested with a within-subjects factorial ANOVA: 2 Marker 1 (L or R) $\times$ 2 Marker 2 (L or R). The results showed no significant difference between L and R for the Marker 1 effect [$F(1,7) = .49$] or the Marker 2 effect [$F(1,7) = .32$], but the interaction was significant [$F(1,7) = 14.01, p < .01$]. Both L-L and R-R conditions led to better discrimination than did both bilateral presentations. An additional statistical test confirmed that the L-R (*SD* = 120.3) versus R-L (*SD* = 120.7) difference on sensitivity was not significant [$t(7) = .02$]. However, the L-L (*SD* = 70.3) and R-R (*SD* = 80.3) conditions differed significantly [$t(7) = 3.17, p < .05$].

Discussion

The basic question in this experiment was to relate sensitivity to perceived duration. Two comparisons are of interest: the unilateral versus the bilateral sequences and the R-L versus the L-R sequences.

In this experiment, there was no systematic tendency to perceive unilateral sequences as being shorter than bilateral sequences. Nevertheless, discrimination was systematically better with both unilateral sequences than with both bilateral sequences. This large sensitivity difference between unilateral and bilateral conditions is consistent with the results of Grondin and Rousseau (1991, Experiment 1). They observed better discrimination with two visual markers delivered from the same place on the periphery than with one visual signal on the periphery, either Marker 1 or Marker 2, and the other at fovea.

Regarding the comparisons of bilateral intervals, the R-L sequence was perceived as being shorter than the

Figure 1. Mean adaptation level (minus 250) for each marker-type condition of Experiment 1. Error bars are standard error. One value below 0 msec (horizontal line) indicates more "long" than "short" responses; the values above the line indicate more "short" than "long" responses. (L, left; R, right.)

Figure 2. Mean sensitivity (1 SD) for each marker-type condition of Experiment 1. Error bars are standard error. (L, left; R, right.)

L-R sequence. However, there was no difference between these conditions with regard to sensitivity.

Taken together, the results summarized in the last two paragraphs indicate that the parallel proposed between the total accumulation of time pulses and the variability of this accumulation over trials is not straightforward. Such an inconsistency between perceived duration and sensitivity was also observed earlier with intermodal intervals where marker length was varied (Grondin, Ivry, Franz, Perreault, & Metthé, 1996). This suggests that some nontemporal sources of variance are critical in duration discrimination.

Regarding the different sensitivities of the uni- versus bilateral intervals, one can argue that there is a fundamental difference between these conditions because there is space involved with bilateral sequences. Indeed, there are phenomena well known for showing interactions between time and space in the visual mode. One is the apparent movement (or the phi phenomenon: Wertheimer, 1912/1961). Another important one is the kappa effect, which is observed when space is taken into account in the perception of duration. (Note that its mirror-image, when duration affects perceived distance, is called a tau effect.) In most studies showing the kappa effect, there is a sequence of three flashes spatially separated in order to determine two time intervals (Collyer, 1977; Jones & Huang, 1982). Although only two flashes (one interval) were used in our experiments, the possibility that distance influences time judgments cannot be ruled out. However, the kappa effect, as well as apparent movement, would not help to explain the L-R versus R-L asymmetry for perceived duration. Also, if discrimination had been better with bilateral than with unilateral sequences, one could argue that the difference depended on the fact that only the bilateral sequences could benefit from an efficient mechanism involving space. In the present experiment, it is clearly shown that it is with the unilateral sequences that discrimination is better.

Regarding the AL results, the significant difference between the bilateral conditions is interesting in itself.

Indeed, the present interpretation of the results relies on the assumption that the subjects, who were presented with feedback after each trial, adopted a common criterion for all experimental conditions. We attribute the different distributions of short and long responses in the R-L and L-R conditions to a difference of perceived duration. This difference might well be caused by differences in the moments when a subject starts and stops the timing activity, which, in turn, might depend on an attention bias in the processing of the signal (Sekuler et al., 1973). A bias toward the left would favor an earlier internal onset with Marker 1 to the left visual field and a later internal offset with Marker 2 to the right visual field. Consequently, and according to the internal-clock view reported earlier, if the timing period starts earlier (Marker 1 to the left) and stops later (Marker 2 to the right), more pulses emitted by the pacemaker will be accumulated (longer perceived duration) than if the timing starts later (Marker 1 to the right) and stops earlier (Marker 2 to the left). That would explain why the L-R sequence was perceived as lasting longer than the R-L sequence.

What is more impressive in the R-L versus L-R difference reported in the present experiment is the magnitude of the effect, about 50 msec. This is much more than what would be expected from the left-to-right scanning mechanism proposed by Sekuler et al. (1973). Although the large difference in the present experiment might depend on the magnitude of the distance between the visual signals, such a difference is more compatible with an attention bias toward the left. Stelmach and Herdman (1991), using a temporal order task, have reported that directing attention could affect transmission latencies of visual signals by about 40 msec.

EXPERIMENT 2

Three issues were addressed in Experiment 2. First, we sought to replicate the findings of Experiment 1 regarding the uni- versus bilateral sequences and the R-L versus L-R sequences. Second, we tested the effect of uncertainty on the sensitivity of subjects. Third, we compared unilateral sequences with a condition in which markers were presented at fovea. Given that the number of experimental conditions was increased from 4 to 9 in Experiment 2, we decided to adopt the model proposed in signal detection theory (SDT) to estimate the sensitivity and perceived duration of the subjects.

Method

Subjects. Sixteen subjects participated in this experiment. One was the author, tested at Laval, and 15 were 20- to 38-year-old university student volunteers. Eight were students at Laurentian University and 7 were at Laval University. They all received \$27 (Canadian) for their participation. Only consistent right-handers, based on the handedness portion of the questionnaire of Coren (1993), were selected.

Apparatus and Stimuli. The material was the same as in Experiment 1 and was the same for the Laval and Laurentian portions of the experiment. The LED placed in front of the subject in Ex-

periment 1 was used in the last session of Experiment 2. This LED had the same features as the LEDs placed in the periphery.

Procedure. The main change in Experiment 2 was in the procedure. Since the number of experimental conditions was increased, it was decided to adopt a procedure requiring fewer trials to estimate the parameters of interest. In Experiment 1, although there was no presentation of the standard for each trial, the procedure was like that of the method of constant stimuli (MCS), which allowed us to estimate sensitivity and to quantify relative perceived durations on the basis of psychometric functions. The MCS is known to require many trials and to be time consuming.

Each trial was conducted as in Experiment 1, which included feedback, but only one short (220 msec) or one long (280 msec) interval was presented. There were nine sessions, divided into three parts, two parts of four sessions and one part of one session (Part 3, i.e., Session 9). In Parts 1 and 2, the subjects were tested in the same four marker-type conditions as in Experiment 1. In one part, the test was identical across session since the subjects did not know the locations (L or R) of Marker 1 or Marker 2 (the uncertainty condition). For this uncertainty condition, the four sessions were identical: four blocks of 64 trials, with eight presentations within each block, in a random order, of the eight conditions (L-L, L-R, R-L, R-R; at 220 and 280 msec).

In four other sessions, one per marker-type condition (L-L, L-R, R-L, R-R), the subjects knew that, for a complete session, the marker conditions remained the same (the certainty condition). In each session, there were also four blocks of 64 trials, with 32 repetitions, in a random order, of the short and long intervals.

For the subjects from Laurentian, before each certainty session, 10 presentations were made of a 250-msec interval in the appropriate marker condition in order to reduce any influence from previous sessions. The subjects knew that these intervals were at midpoint between the short and long intervals. For these presentations, the subjects made no responses and there was no feedback. Before each certainty condition, the subjects tested at Laval had 10 practice trials that were similar to the experimental trials.

The order of presentation of the four certainty sessions was balanced according to a Latin square. Four subjects tested at Laurentian and 4 tested at Laval began with the certainty condition first (Sessions 1-4) and ended with the uncertainty condition (Sessions 5-8); 4 subjects tested at Laurentian and 4 tested at Laval had the reverse order.

For all subjects, a ninth and last session was devoted to another marker-type condition: both markers were presented in front of the subject (fovea-fovea condition: F-F). The procedure in Session 9 was the same as that used for the certainty sessions. In all sessions, there were 15 sec between the blocks, and each session lasted about 20 min.

Dependent variables. Here, as in Experiment 1, there are two dependent variables of interest: sensitivity and perceived duration. In the present experiment, sensitivity was estimated using the parameter d' of SDT, on the basis of three assumptions: The subjects used a fixed criterion, the distributions for the short and long signals were normal, and they had equal variances. Indeed, these distributions are the noise (N) and signal + noise (SN) distributions in the SDT. In the present experiment, a hit was responding "long" when the interval was long, and a false alarm was responding "long" when the interval was short.

The d' can be computed by subtracting Z_{SN} from Z_N , where Z_{SN} is the Z transformation of 1 minus the proportion of hits, and Z_N is the Z transformation of 1 minus the proportion of false alarms (Gescheider, 1985).

For estimating the magnitude of the perceived duration in different marker-type conditions, we used β . For one given observation, β is the likelihood ratio of the ordinate of the SN distribution to the

ordinate of the N distribution. A high value of β indicates a bias towards responding "short."

Note that the present interpretation of the β values is not traditional. Usually, β is a decisional criterion; it reflects the effect of some variables like the set, attitude, or motives of an observer (Swets, Tanner, & Birdsall, 1961). Indeed, it reflects a judgmental (or cognitive) component, not a perceptual component. In the present analysis, the situation is the reverse. Multiple β values are not interpreted here as reflecting the use of multiple criteria. Instead of having β shifting on the x-axis, with different experimental conditions, for one given situation with N and SN distributions, we assume that for all experimental (marker-type) conditions, the observer uses one criterion. No manipulations, such as variations of the probability of occurrence of a signal or the payoff for hits and punishment for false alarms, were used in the experiment. These manipulations are known to provoke shifts on the location of the criterion. Therefore, we assume that the β values are not related to subjects' cognitive strategies. Rather, it is the N and SN distributions of each experimental condition that are assumed to be located at different levels on the x-axis; and it is further assumed that, for one given experimental condition, the shift is the same for both N and SN distributions. In other words, in the present analysis, β is interpreted as reflecting a perceptual phenomenon.

d' and β were computed on the basis of the presentation of 128 short and 128 long intervals in each marker-type condition, using the computer program reported by Macmillan and Creelman (1991, Appendix 6).

Results

Two dependent variables are of interest: the tendency of subjects to respond "long" and sensitivity. These variables are estimated using β and d' .

Regarding perceived duration, the results show that it was in the L-R condition that subjects responded "long" most often and in the R-R condition that they responded "short" most often. Given that the distribution of β values around the mean cannot be assumed to be symmetric, the statistical analysis was performed on their log values, which allow one to assume a normal distribution of scores. Figure 3 shows the mean log β in each experimental condition for both certainty and uncertainty con-

Figure 3. Mean beta (in log value) for each marker-type condition in the uncertainty condition of Experiment 2. Error bars are standard error. The values below 0 (horizontal line) indicate more "long" than "short" responses; the values above the line indicate more "short" than "long" responses. (L, left; R, right; F, fovea.)

ditions. Deviations from 0 are much more evident in the uncertainty condition, which is the expected consequence of the direct comparison of the perceived length of the different marker-type intervals.

A 2 (Marker 1) $\times$ 2 (Marker 2) ANOVA, according to a within-subjects factorial design, was conducted on the results for the uncertainty condition. With a significance level set at $p < .05$, the analysis revealed no main effect for Marker 1 [$F(1,15) = 3.54$] or for Marker 2 [$F(1,15) = .50$] and no interaction effect [$F(1,15) = 4.22$]. Finally, a statistical analysis restricted to the R-L and L-R conditions showed that, as in Experiment 1, subjects responded "long" more often in the L-R condition [$t(15) = 3.65, p < .01$].

Regarding the sensitivity results (d'), several observations are noteworthy (see Figure 4). The L-R and R-L sequences seem to be about equally well discriminated, and these two conditions provided worse discrimination than both unilateral conditions. Moreover, for all marker-type conditions, there are some differences between the certainty and uncertainty conditions. Finally, in the F-F condition, discrimination appears better than in both the L-L and the R-R conditions.

An ANOVA with a 2 $\times$ 2 $\times$ 2 within-subjects factorial design was used to test the significance of the difference between the mean d' in the various experimental conditions (2 Marker 1, 2 Marker 2, and 2 certainty-uncertainty). The F-F condition is not included in this ANOVA. No main effect was significant, but the Marker 1 $\times$ Marker 2 interaction was significant [$F(1,15) = 85.50, p < .01$]. This effect indicates higher sensitivity with both unilateral sequences over both bilateral sequences. No other interaction effect was significant. A t test was conducted to compare the F-F ($d' = 2.09$) condition with the average results of the R-R ($d' = 1.61$) and L-L ($d' = 1.60$) conditions observed under the certainty condition. The difference was significant [$t(15) = 2.52, p < .05$]. However, the RR and LL conditions do not differ significantly. Finally, for the uncertainty condition, the L-R

($d' = 1.05$) and R-L ($d' = .94$) difference was directly tested with a t test, and the difference is not significant [$t(15) = 1.53$].

Discussion

The purposes of Experiment 2 were to replicate findings of Experiment 1, and to verify whether or not using uncertainty conditions and peripheral stimuli affected sensitivity.

As in Experiment 1, an R-L sequence was shown to be perceptually shorter than an L-R sequence. Nevertheless, the results on perceived duration were not completely consistent in both experiments. In Experiment 1, the bilateral conditions were the extreme cases, that is, the conditions showing the shortest and longest perceived durations. In the present experiment, both unilateral intervals were perceived as being the shortest. This inconsistency might depend on the fact that two different factors could be determining the resulting effect. On the one hand, as noted earlier, it is possible that an attention bias influences the speed of processing of the signals. A bias toward the left would favor an earlier internal onset with Marker 1 to the left and a later internal offset with Marker 2 to the right. This should result in the tendency, observed in both experiments, to have an L-R sequence perceived as being longer than an R-L one. On the other hand, it is possible that some priming effect occurs with the unilateral conditions. The presence of the first signal might enhance the transmission speed of a second signal delivered at the same location. The literature on priming (Posner, 1978) described this effect as the activation produced by a first signal resulting in a more rapid encoding of an identical second signal. The encoding could be cognitive or sensory. In the context of duration discrimination, if there is any priming effect, it would be at a sensory level. However, as noted by Krueger and Shapiro (1981), there are reasons, such as satiation or decreased alertness, to expect stimulus repetition to hinder perceptual processing.

Regarding sensitivity, there was a clear interaction between Markers 1 and 2, as in Experiment 1, revealing that the bilateral intervals (L-R or R-L) were discriminated more poorly than the unilateral ones (R-R or L-L). Thus, in Experiment 2, unilateral sequences were both perceived as being shorter and better discriminated than the bilateral sequences. This is consistent with the prediction reported earlier: Variability should increase as a function of the mean number of accumulated pulses generated by a pacemaker.

Sensitivity was not affected by the certainty versus uncertainty manipulation. Grondin and Rousseau (1991, Experiment 2) have reported that duration discrimination is not impaired by uncertainty about only one marker, the first or the second, when the signal could be delivered from one of three sensory modes, visual, tactile, or auditory. However, in the same article (Experiment 1), overall sensitivity is reported to decrease when both Marker 1 and Marker 2 can be delivered from four possible sig-

Figure 4. Mean sensitivity (d') for each marker-type condition in the certainty and uncertainty conditions of Experiment 2. Error bars are standard error. (L, left; R, right; F, fovea.)

nals, two auditory and two visual. The magnitude of the uncertainty, that is, 16 possible marker types for each trial, induced this deterioration. In the present experiment, and presumably in Experiment 1, the uncertainty was not important enough to affect sensitivity.

Finally, one might have expected better discrimination when both signals were presented at fovea rather than at the periphery. Visual acuity is known to be at its maximum at fovea. Thus, signals delivered in this area, being more clearly detected, should contribute a low variance to the marking process of an interval. Our results do allow us to conclude that a sequence of two flashes is better discriminated if they are delivered at fovea rather than at the periphery. This result is consistent with the tendency observed by Grondin and Rousseau (1991, Experiment 1). This effect might be due to attention. Since subjects were asked to look in front of them, visuospatial attention to the foveal stimulus is probably increased, facilitating the processing of sensory information (Hawkins et al., 1990).

EXPERIMENT 3

The very large sensitivity difference between the unilateral and the bilateral intervals, consistent in both experiments, recalls the fact that using intermodal markers is known to severely affect duration discrimination (Grondin & Rousseau, 1991; Rousseau, Poirier, & Lemyre, 1983) and gap detection (Collyer, 1974). An intermodal interval is an empty interval marked by signals delivered from two different sensory modes.

The data in the present study suggest that the intermodal problem might not be intermodal per se. Using visual stimuli with a large distance between Markers 1 and 2 produces an effect comparable to that of intermodal conditions. In Experiment 1, 1 *SD* in the bilateral conditions was over 100 msec. Reported on the same basis (1 *SD*), the results of Grondin et al. (1996, Experiments 2 and 3) with visual-auditory or auditory-visual sequences are about the same. Also, the results of Experiment 2 show d' values slightly higher than 1 with a 60-msec difference between the short and long intervals. This is superior to d' values of about .60 in Rousseau et al. (1983) and .80 in Grondin and Rousseau (1991), but those results were obtained with a 50-msec difference between the short and long intervals.

One goal of the present experiment was to test directly the relative perceived duration and sensitivity of bilateral versus intermodal sequences. The experiment also provided a new comparison of the L-R versus R-L conditions and a comparison of two types of intermodal intervals.

Method

Subjects. Twelve subjects participated in this experiment. One was the author and 11 were 21- to 34-year-old Laval University student volunteers who were paid \$16 (Canadian). Seven of them had participated in Experiment 2. As in Experiment 2, only consistent right-handers were selected.

Apparatus and Stimuli. The material was the same as in the previous experiments. The auditory signal (A) was a 1-kHz tone with an intensity recorded at about 70 dB SPL. The signal was presented binaurally for 20 msec through a headphone (Sony MDR-V600).

Procedure. Each trial was conducted as in Experiment 2, which included feedback, but the short and long intervals lasted 210 and 290 msec, respectively. This increase in the difference between the short- and long-interval values was introduced because the task, which involved six marker-type conditions, was expected to be more difficult. The six marker-type conditions were the following: L-R, R-L, A-L, L-A, A-R, and R-A. Thus, there were no L-L, R-R, or A-A sequences presented. As in the previous experiments, the subjects were required to fixate a point in front of them, located midway between the L and R LEDs.

There were four sessions divided into four blocks of 96 trials. Within each block, each of 12 conditions (6 marker types $\times$ 2 intervals, short or long) was presented eight times in a random order. Each session lasted about 30 min.

Results and Discussion

The dependent variables of interest here are, as in Experiment 2, β (perceived duration) and d' (sensitivity). They were estimated on the basis of the presentation of 128 short and 128 long intervals for each marker-type condition. The mean results for each marker-type condition are reported in Figure 5 (perceived duration) and Figure 6 (sensitivity).

For each dependent variable, three planned comparisons were of interest: bilateral versus intermodal sequences, L-R versus R-L sequences, and auditory-visual versus visual-auditory sequences.

For the first comparison, the mean of the L-R and R-L conditions was compared with the mean of the four intermodal intervals (L-A, A-L, R-A, and A-R). The bilateral sequences were systematically perceived as being longer than the intermodal ones. The difference is significant [$t(11) = 5.92, p < .01$].

If intervals perceived as being shorter are easier to discriminate, intermodal intervals should be easier to discriminate. This is not what Figure 6 shows. Indeed, the

Figure 5. Mean beta (in log value) for each marker-type condition in Experiment 3. Error bars are standard error. The values below 0 (horizontal line) indicate more "long" than "short" responses; the values above the line indicate more "short" than "long" responses. (L, left; R, right; A, auditory.)

Figure 6. Mean sensitivity (d') for each marker-type condition in Experiment 3. Error bars are standard error. (L, left; R, right; A, auditory.)

mean d' is 1.32 for bilateral sequences and .95 for intermodal sequences, and this difference is significant [$t(11) = 3.00, p < .02$].

The direct comparison of the bilateral sequences indicates that the L-R sequence only tends to be perceived as being longer than the R-L sequence. The difference is not significant [$t(11) = .87, p = .40$]. Only 8 of 12 subjects showed longer perceived durations with the L-R sequence. Introducing an auditory signal in the marker conditions in Experiment 3 might have produced a reorganization of visuospatial attention. Finally, sensitivity is about the same with the R-L and L-R sequences [$t(11) = .74, p = .48$].

Regarding the intermodal intervals, the mean of the visual-auditory (V-A: L-A and R-A) sequences was compared with the mean of auditory-visual (A-V: A-L and A-R) sequences. There is some difference in the perceived duration of these sequences. Indeed, for the 24 A-V versus V-A individual comparisons available in the present experiment (12 subjects for L-A vs. A-L, and the same 12 subjects for R-A vs. A-R), 16 showed shorter durations in the V-A than in the A-V conditions. However, this difference is not significant [$t(11) = .55, p = .59$].

It is noteworthy that the individual differences for the perceived durations of A-V versus V-A sequences are extremely striking. For instance, Subject 1 showed β values equal to 4.71 and .60, respectively, in the R-A and A-R conditions, whereas Subject 9 showed .84 and 3.18 in the same conditions. Literature on this issue reveals that the A-V intervals are perceived as being longer than the V-A intervals (Grondin et al., 1996; Grondin & Rousseau, 1991, Experiment 1).

Two methodological factors might explain why there is no V-A versus A-V difference for perceived duration in the present experiment, while previous reports showed that a V-A sequence is perceived as being shorter than an A-V sequence. First, for both Marker 1 and Marker 2 in the present experiment, the probability was three

times greater for having a visual than for having an auditory signal. This might divert attention toward the visual mode. Thus, if Marker 1 is auditory, the beginning of the pulses' accumulation period might be delayed, which would result in a shorter perceived duration of an A-V sequence.

Second, the fact that both visual markers were delivered from the periphery in the present experiment might also have influenced the results. Pease and Sticht (1965) have reported that reaction time to the onset and to the offset of a visual stimulus is influenced by the location, fovea or periphery, of the signal. Also, Grondin and Rousseau (1991) have reported that having the second marker of an A-V sequence delivered at the periphery rather than at fovea greatly reduces the perceived duration of such a sequence; along the same line, they also have reported that, in a V-A sequence, the perceived duration is much shorter when the first marker is delivered from the periphery rather than from fovea.

Regarding the sensitivity of the A-V versus V-A sequences, there was no significant difference [$t(11) = .12, p = .91$]. This is consistent with Grondin et al. (1996), who found that although discrimination is generally better in the V-A than in the A-V for intervals of 500 and 750 msec, it is about equal at 250 msec. For this range of duration, Rousseau et al. (1983) have reported no discrimination difference between the A-V and V-A conditions; Grondin and Methé (1993), however, have reported better discrimination in the A-V condition.

Finally, note that, for the subjects whose individual results for perceived durations are reported above, there was virtually no sensitivity difference related to the order of the sequence. For Subject 1, d' values were 1.66 and 1.61, respectively, in the L-A and A-L conditions; for Subject 9, the sensitivity was 1.34 in both cases.

GENERAL DISCUSSION

The results of three experiments reveal important information about duration discrimination. Experiments 1 and 2 showed clearly that unilateral intervals are better discriminated than bilateral ones, but only in Experiment 2 was the perceived duration shorter with both unilateral sequences than with both bilateral sequences. In both Experiment 1 and Experiment 2, the duration of a sequence of two visual signals was perceived as longer for an L-R than for an R-L order, but those sequences were equally well discriminated. In addition, in Experiment 2, randomizing the location of Markers 1 and 2 from trial to trial did not significantly affect duration discrimination. Moreover, this experiment also showed that unilateral sequences were not as well discriminated as were intervals marked by an F-F sequence. Finally, Experiment 3 showed that the bilateral sequences employed throughout the present study provided better duration discrimination than did intermodal sequences, although intermodal intervals were perceived as being shorter than the bilateral ones.

About Time Psychophysics

The main issue addressed in this article was the link between perceived duration and sensitivity. In time psychophysics, sensitivity is determined mainly by the properties of an internal clock. This clock is often described as a pacemaker-counter device (Killeen & Weiss, 1987). The accumulation of pulses generated by a pacemaker is the basis of time experienced. Thus, the more pulses accumulated, the longer the perceived duration; and the variability of the emission of pulses is said to be the main source of errors. Moreover, variability should increase as a function of the mean number of pulses accumulated—that is, the perceived duration.

In general, the data of the present series of experiments do not allow us to link sensitivity (variability) and perceived duration directly. For instance, the comparison of results in the R–L and L–R conditions, in both Experiment 1 and Experiment 2, reveals an inconsistency with the internal-clock view proposed above. The perceived duration of an L–R sequence is longer than that of an R–L sequence. If perceived durations depend on the numbers of pulses accumulated and variability of judged duration is proportional to the mean number of pulses, then longer perceived durations should be accompanied by more variability. In other words, more variability should occur with an L–R than with an R–L sequence because the former is perceived as longer. The data indicate that, when intervals are marked bilaterally, the nontemporal factors are sources of variance at least as important as is the variability of pulse emissions. The exact nature of these nontemporal factors remains to be specified and their relative contribution, to be quantified.

Explaining the unilateral versus bilateral results can only be tentative at this point, as are explanations for intermodal results. Rousseau et al. (1983) have proposed an internal-distance interpretation for the weak discrimination of intermodal intervals, consistent with a central-timing hypothesis. In their view, intermodal intervals require both sensory signals (markers) to reach a given temporal processing space in order to allow for discrimination. The variability in the timekeeping process increases with the latency of the signals, this latency increasing with the distance to reach this space. This view would account for the different sensitivities observed with uni- versus bilateral sequences in Experiments 1 and 2. It would also account for better discrimination with bilateral sequences than with intermodal sequences (Experiment 3), assuming that the distance to reach this processing space is longer for intermodal intervals than for bilateral visual sequences.

There is also one alternative hypothesis that could account for the different levels of sensitivity observed with different marker-type conditions. Collyer (1974) has proposed that using intermodal conditions might represent the operation of a central temporal discrimination mechanism whereas using an intramodal sequence might provide nontemporal cues originating in the peripheral system (auditory in his experiment). Transposing this ex-

planation to visual-mode conditions, unilateral intervals would provide peripheral cues, whereas bilateral intervals, as well as intermodal intervals, would require central processing.

Moreover, as noted in the discussion of Experiment 1, the question of using space in the visual field (the apparent movement or kappa effect) as a cue to judge time cannot be totally ruled out. The superior discrimination of bilateral over intermodal sequences (Experiment 3) would depend on the fact that, in the former case, space can be taken into account, whereas, in the latter case, it is unlikely.

Laterality and Timing

Literature on temporal processing and laterality offers a series of data consistent with the hypothesis that a timer is located in the left hemisphere (LH). This hypothesis is particularly appealing considering, as noted by Efron (1990), that time sense and language are associated, because (1) language requires a temporal ordering of sequences of sounds, and (2) its cerebral location is known to be also the LH. Considerable evidence shows the role of the LH in the judgments on temporal order, gap detection, and simultaneity or successiveness (Efron, 1963; Mills & Rollman, 1980; Nicholls, 1994), and there are reports consistent with an LH-timer hypothesis for the estimation of brief intervals (Mills & Rollman, 1979; Polzella, DaPolito, & Hinsman, 1977) and interval production (Sergent, Hellige, & Cherry, 1993).

On the other hand, there is one report suggesting a right-hemisphere (RH) superiority for duration discrimination of tones (Buchtel, Rizzolatti, Anzola, & Bertoloni, 1978). When asked to discriminate between short (50 and 100 msec) and long intervals (200 and 400 msec), subjects had faster reaction times when tones marking the intervals were presented to the left (RH) rather than to the right (LH) ear. However, there was no hemispheric difference for the same task when markers were stationary visual stimuli (Bertoloni, Anzola, Buchtel & Rizzolatti, 1978). It is important to emphasize the fact that the dependent variable in the experiments reported by Buchtel et al. (1978) and Bertoloni et al. (1978) was reaction time. No data, such as difference threshold, d' , or percentage of correct responses, are reported regarding the relative capability of each cerebral hemisphere to perform duration discrimination.

The data reported in the present series of experiments can hardly support an LH-timer hypothesis. This hypothesis suggests certain predictions for the duration discrimination of empty intervals marked by visual signals delivered to the left or to the right of a fixation point in the visual field. With a lateralized timer, it is assumed that the signals marking an interval must reach the appropriate hemisphere in order to allow for temporal processing. With an LH timer, presenting markers in the left visual field (LVF) requires a transcallosal transmission of the signals. Assuming that this transmission would produce a degradation of information (Kimura, 1966), extra vari-

ance in the processing of such signals is expected. Consequently, discrimination should be better with an R–R than with an L–L sequence, given that signals delivered in the right visual field (RVF) directly reach the LH. However, data from Experiment 2 showed no sign of a difference between L–L and R–R sequences, and data from Experiment 1 even showed a slightly better discrimination for intervals marked by signals delivered in the LVF.

The transcallosal transmission also takes time (Efron, 1990), which might have an effect on the perceived length of intervals. With bilateral sequences and an LH timer, the timing activity should start earlier if Marker 1 is delivered in the RVF rather than in the LVF, and should stop later if Marker 2 is delivered in the LVF rather than in the RVF. Consequently, we can predict a longer perceived duration with an R–L than with an L–R sequence. However, the results of both Experiment 1 and Experiment 2 went the opposite way.

Different suggestions are proposed below to provide an alternative approach to the LH-timer hypothesis, suggestions that should be considered in developing a full explanation for lateral effects on timing. First, having data going in the opposite direction of what an LH-timer would predict leads us to propose an RH-timer for duration discrimination. This hypothesis is not completely implausible considering that musical performance, a skill that requires precise timing, has often been reported to be in the RH's domain (Bradshaw & Nettleton, 1981; Peretz, 1993). However, we observed better discrimination with an R–R sequence, where neither marker would be delivered to the hemisphere specialized for timing, than with an L–R or R–L sequence, where one of the signals would arrive directly to the RH. Any further development of an RH-timer hypothesis has to deal with this inconsistent result.

The second and third propositions below rely on the idea that timing might be possible in both hemispheres. Polzella et al. (1977) did not reject this possibility. These two propositions differ in the identification of the main source of variance for duration discrimination.

On the one hand, there might be a fundamental difference in the way each hemisphere processes temporal information. It is generally established in neuropsychology that the LH is associated with language and analytic functions, whereas the RH is more specialized in visuospatial functions and processes stimuli in a holistic and synthetic mode (Bradshaw & Nettleton, 1981). A tentative explanation of any R–R and L–L sequence differences is that the RH, contrary to the LH, might process the succession of two flashes as a global organization. With such a view, the L–L versus R–R sensitivity difference would reflect the relative efficiencies of the LH and RH timers. Also, the superiority of the unilateral sequences over the bilateral ones would be explained by the interhemispheric transfer of one signal. Finally, the different perceived durations with bilateral sequences would

reveal that, if both markers are not delivered in the RVF, time is processed in the RH.

On the other hand, timing might be possible in both hemispheres and the temporal mechanism might be identical. However, the efficiency of processing the sensory signals might not be the same. The visible persistence of a brief stimulus might not be different in both hemispheres (Di Lollo, 1981), but a bias in attention toward the left should not be ruled out (Sekuler et al., 1973). Visuospatial attention is reported to facilitate the processing of sensory information (Hawkins et al., 1990). Such a bias would favor an L–L sequence over an R–R sequence, which is consistent with the tendency reported in Experiment 1. Attention bias toward the left would also explain the unequal perceived durations with bilateral sequences observed in both Experiment 1 and Experiment 2, because the timing period would start earlier with Marker 1 delivered to the left than it would to the right visual field. Finally, the uni- versus bilateral differences for sensitivity would also depend on the interhemispheric transfer of a signal.

Conclusion

The present study showed that even when intervals to be discriminated remain marked by signals delivered within the same mode, the marker conditions produce a large variety of discrimination levels. Using a large distance between visual signals, instead of two signals delivered from the same source, impairs discrimination (Experiments 1 and 2). The worst discrimination was observed with intermodal intervals (Experiment 3). This can be viewed as the result of a common mechanism of timing where the relative influence on sensitivity of nontemporal factors increases from little (unilateral sequences) to a lot (intermodal intervals), with potential points in between related to the separation of signals (such as bilateral sequences). However, sensitivity is not directly related to perceived duration. Bilateral sequences were perceived as longer than both unilateral (Experiment 2) and intermodal (Experiment 3) sequences, but led to more variability than the unilateral sequences only.

An analysis such as the one proposed in the present article, where both sensitivity and perceived duration were taken into account, is critical for testing the single-timer hypothesis proposed in time psychophysics (Allan, 1979). The results of the present series of experiments reveal that the relative importance of the fluctuations of pulse emissions by the pacemaker, in the total account of sensitivity levels, decreases very much as nontemporal factors intervene in the duration-discrimination process. Understanding this link between sensitivity and perceived duration, within the scope of this single-timer hypothesis, cannot be made on the strict basis of a simple sensory explanation. More remains to be specified on the effect of attention on the processing of temporal information (Grondin & Macar, 1992; Macar et al., 1994; Mattes & Ulrich, 1994) and on the processing of the markers. For

instance, studies on cross-modal links in the orienting of covert attention reveal that audition influences vision, but not vice versa (Spence & Driver, 1997). This type of nonreciprocal link probably has a direct impact on the processing of intermodal intervals. Moreover, the animal literature shows the critical role of memory processes on duration discrimination (Gibbon, Church, & Meck, 1984). Memory involvement is also probably a critical source of variance in human duration discrimination, and this issue deserves further empirical investigation.

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