Perception, 2009, volume 38, pages 1542 – 1559

doi:10.1068/p6359

Duration discrimination in crossmodal sequences

Simon Grondin
École de Psychologie, Université Laval, Québec, QC G1A 0V6, Canada;
e-mail: simon.grondin@psy.ulaval.ca

J Devin McAuley
Department of Psychology, Michigan State University, East Lansing, MI 48824, USA;
e-mail: dmcauley@msu.edu
Received 23 December 2008, in revised form 10 May 2009; published online 6 October 2009

Abstract. Four duration-discrimination experiments were carried out to compare crossmodal and unimodal timing conditions. For all experiments, participants were presented with two sequences, each consisting of 1 or 4 time intervals (marked by 2 or 5 signals), and asked to indicate whether the interval(s) of the second sequence was (were) shorter or longer than the interval(s) of the first. Markers in the first and second sequences were, respectively, tones and flashes (experiment 1), flashes and tones (experiment 2), both flashes (experiment 3), and both tones (experiment 4). In all modality conditions, except when using only tones (experiment 4), increasing the number of repetitions of the variable interval reduced duration-discrimination thresholds, independently of whether the fixed interval was presented first or second within the sequence pair. Moreover, judgments about sequence timing were best for tones – tones sequence pairs, worst for flashes – flashes sequence pairs, and intermediate for crossmodal (flashes – tones or tones – flashes) sequences. Finally, presenting a fixed interval in the first sequence resulted in better discrimination than presenting a variable interval in the first sequence. Implications for theories of timing are discussed.

1 Introduction

Animals receive continuous sensory stimulation, which provides information about objects and events in the world. Animals must coordinate the flux of information received by the different senses in order to develop coherent and stable perceptions (Bahrick and Lickliter 2000; Bahrick et al 2004). Many aspects of the world are modality-specific in that they can only be conveyed through a single sense (eg the color of an object). However, other properties of the world, such as the rate, rhythm, or duration of an event, are amodal properties that can be conveyed by multiple senses (eg the duration of an event can be marked by either sights or sounds). For humans, sensitivity to the amodal temporal properties of events is important for the success of many time-critical behaviors, such as crossing a busy street, playing a game of basketball, performing on a musical instrument, or carrying on a conversation. The general aim of this article is to contribute to the understanding of mechanisms involved in processing temporal information. Of particular interest is a comparison of duration discrimination in crossmodal and unimodal timing conditions.

The nature of the processes involved in timing and temporal processing has a long history in experimental psychology (Roeckelein 2008; Woodrow 1951). To account for the timing capabilities of humans and other animals, many researchers refer to the notion of an internal clock. This clock is frequently described as a pacemaker-counter device (Creelman 1962; Treisman 1963; see Killeen and Weiss 1987). According to this perspective, the pacemaker emits pulses according to some distribution property (see Grondin 2001b, for a review) and the accumulation of these pulses determines the subjective experience of time: the more pulses accumulated the longer the perceived duration.

The pacemaker-counter view is often embedded within a general information-processing modeling framework developed by Gibbon, Church, Meck and colleagues, which has been used to explain various aspects of performance in studies of both human and non-human animal timing (Church 1984; Gibbon and Church 1984; Gibbon et al 1984; Meck 2003). Within the information-processing framework, duration-discrimination errors are related to at least one of three levels of processing: perceptual (the clock), mnemonic, and decisional. Factors that impact duration-discrimination errors (or conversely favor better duration-discrimination performance) provide important clues about the properties of the internal clock and the nature of the different sources of error. Central to this investigation is the impact of the two factors on duration-discrimination thresholds: (i) the sensory modality of time-marking events (auditory versus visual), and (ii) the number of time-marking events.

There is a long tradition in time psychophysics of presenting a single time interval marked by the successive onsets of two discrete events (an empty interval) and asking an observer to assign this interval into the appropriate category (short or long), or to present two empty intervals and asking an observer to judge their relative duration (see Grondin 2008). It is known that the sensory modality used to mark the intervals affects performance levels (Grondin 2003). For instance, the discrimination of intervals is much better when events are marked by auditory rather than by visual or tactile signals, but is severely impaired when signals from two different modalities mark the beginning and end of a single empty interval (Grondin 1993; Grondin and Rousseau 1991). An issue that has received less attention is an individual's ability to make crossmodal comparisons of durations (eg a time interval marked by signals in one modality compared with a time interval marked by signals in a different modality—van Erp and Werkhoven 2004; Ulrich et al 2006). This type of question is fundamental as one might argue that, if there is a central (amodal) clock, using signals from different modalities should not have much impact on performance; whereas, if timekeeping activities are modality specific, then crossmodal comparisons should suffer relative to unimodal comparisons.

Outside the laboratory, empty time intervals marked by a pair of discrete events rarely occur in isolation; rather they tend to be embedded within extended temporal sequences, which can in many cases be multimodal or involve crossmodal comparisons. This issue has led to substantive debate about whether the processes involved in duration discrimination for isolated empty intervals are in fact the same as those for judgments about sequence timing.

Typically, timing studies involving sequences present a sequence of n fixed (standard) empty intervals followed by an equal number of variable (comparison) intervals. The designated comparison intervals are presented either in the same sequence as the standard intervals (see for instance ten Hoopen et al 1995) or in a second sequence following an inter-stimulus interval (as in Drake and Botte 1993); in both instances, participants are commonly asked to judge the duration of the variable comparison interval(s) relative to the fixed standard, responding "shorter" or "longer". A robust finding is that duration discrimination is improved when there are repeated presentations of the standard interval (Drake and Botte 1993; Grondin 2001a; McAuley and Kidd 1998; Michon 1964). This result was originally explained by a multiple-look model (Drake and Botte 1993), which, in terms of the information-processing framework described earlier, locates a source of variance at the memory level. According to these authors, a memory trace is created on the basis of the first interval or of the first sequence of intervals. This memory trace, or representation of the interval, forms the basis with which the comparison interval(s) will be contrasted. The model assumes that the prediction of the memory representation improves with the number of standard intervals presented. More specifically, the discrimination level, as expressed by the threshold value, standard deviation (SD), is:

$$\mathrm{SD}_n = \mathrm{SD}_1 (1/\sqrt{n}) \quad (1)$$

where n is the number of intervals.

Results consistent with a multiple-look model have been reported in a number of studies. Multiple-interval advantages have been reported for both auditory and visual sequences for tasks involving time-interval perception as well as production (Grondin 2001a; Ivry and Hazeltine 1995; McAuley and Kidd 1998; Rousseau and Rousseau 1996; ten Hoopen and Akerboom 1983); but in no previous study, however, has the multiple-interval advantage been examined in crossmodal timing conditions. One factor that prevents a clear interpretation of some previous work on the multiple-interval advantage is that the numbers of standard and comparison intervals have sometimes co-varied making the precise reason for improvements in time sensitivity unclear (Drake and Botte 1993; Grondin 2001b; McAuley and Kidd 1998). In this regard, a multiple-interval advantage in sequence timing may occur because of multiple standard intervals, comparison intervals, or both.

Interestingly, only recently have researchers varied the number of intervals in each sequence independently (ten Hoopen et al 2004; McAuley and Miller 2007; Miller and McAuley 2005). With a fixed (standard) interval, specified by the first of two auditory sequences, Miller and McAuley (2005) showed that increasing the number of intervals in the second (comparison) sequence, but not the number of intervals in the first (standard) sequence, improves time sensitivity, which is contrary to the assumption that the locus of the multiple-interval advantage is in the reduced variability of the memory representation of the standard. One caveat to a multiple-comparison (rather than multiple-standard) advantage is that, when the standard interval specified by the first sequence is permitted to vary from trial to trial (a variable standard condition), the number of standard and the number of comparison intervals *both* influence time sensitivity, with more presentations leading to better performance (McAuley and Miller 2007; Miller and McAuley 2005). Improvements in time-discrimination performance with repeated intervals (the multiple-interval advantage) appear to be due not only to increased precision in memory for a standard interval, but also to improvements associated with the comparison process. This pattern of findings has been shown for standard intervals ranging from 300 ms to 700 ms (McAuley and Miller 2007; Miller and McAuley 2005).

In the present study, we extend this work by considering the locus of the multiple-interval advantage in crossmodal timing conditions. Crossmodal timing conditions consisted of either a sequence of auditorily marked intervals followed by visually marked intervals, or the reverse. Previous work suggests that the multiple-interval advantage may not be as strong when intervals in a sequence are marked with visual rather than auditory signals [see Grondin (2001a) or Grondin and Girard (2005) for data involving visual stimuli]. Thus, if sensitivity is much higher with auditory than with visual signals, then using crossmodal conditions provides an opportunity to (i) determine if there is a multiple-interval advantage in crossmodal conditions, (ii) measure the relative contribution of the first and second sequence (marked by auditory or visual signals) to overall discrimination performance, and (iii) compare crossmodal timing performance to equivalent unimodal conditions.

In one of the few studies to examine crossmodal conditions, Ulrich et al (2006), using single intervals and an adaptive method (stable standard and variable comparison intervals), reported better discrimination performance with a fixed (standard) interval marked by visual signals and a variable (comparison) interval marked by auditory signals than when the reverse was true. Complicating this picture, however, Ulrich et al (2006) also observed that, when the fixed standard precedes the variable comparison discrimination performance is generally better than when the fixed standard follows the comparison; see also Lapid et al (2008). Combined, these findings suggest that, in the context of crossmodal and unimodal duration comparisons, the multiple-interval advantage may not depend on which sequence (first versus second) receives more intervals; rather, it may be more related to the fact that it is the variable interval(s) that benefits from multiple presentations.

1.1 *Overview*

Reported in this article are four duration-discrimination experiments involving pairs of sequences marked by auditory and visual events. The task across the four experiments was the same: participants were presented with two sequences, each consisting of 1 or 4 time intervals (marked by 2 or 5 signals), and asked to indicate whether the interval(s) of the second sequence was (were) shorter or longer than the interval(s) of the first. In crossmodal timing conditions, markers in the first and second sequences were, respectively, tones and flashes (experiment 1) or flashes and tones (experiment 2). In unimodal timing conditions, markers were either both flashes (experiment 3) or both tones (experiment 4). In each experiment, participants either experienced a 500 ms fixed standard interval (F) in the first sequence and a variable comparison interval (V) in the second sequence that was 500 ± 15, 45, 75, or 105 ms, or the variable intervals were presented in the first sequence and the fixed standard second. In this article, the two orders will be referred to as the fixed–variable (FV) and variable–fixed (VF) conditions, respectively, with different participants assigned to each of the two orders in each experiment.

2 General method

2.1 *Design*

The experiments implemented a 2 (number of auditory or visual intervals in the first sequence) $\times$ 2 (number of auditory or visual intervals in the second sequence) $\times$ 2 (order) mixed-measures design; $n = 1$ or 4 intervals in the first sequence were crossed with $n = 1$ or 4 intervals in the second sequence yielding the four within-subjects sequence conditions (1 : 1, 1 : 4, 4 : 1, 4 : 4), as illustrated in figure 1. Half of the participants in each experiment were given the FV order and half were given the VF order. The four experiments were associated with four marker-type conditions. In experiment 1, stimuli marking the first and second sequences were tones and flashes, respectively; in experiment 2, they were flashes and tones, respectively; in experiment 3, stimuli were all flashes; and in experiment 4, they were all tones.

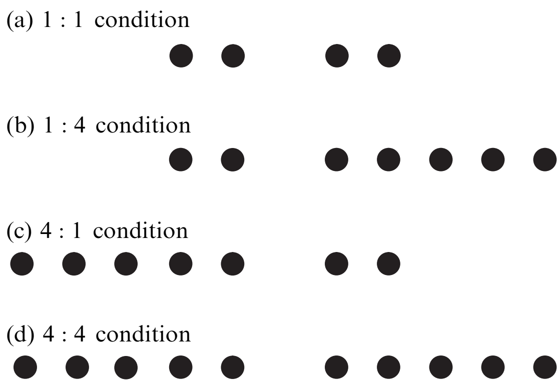

Figure 1. Diagram illustrating the four sequence conditions common to the four experiments. The different conditions are labelled ($n_1 : n_2$) to specify the number of equal intervals in the first sequence (n_1) and the number of equal intervals in the second sequence (n_2). Participants heard fixed-standard–variable-comparison intervals, or variable-comparison–fixed-standard intervals, marked by tones and/or flashes, and judged the relative duration of intervals comprising the second sequence relative to those in the first sequence, responding "shorter" or "longer".

2.2 *Materials and task*

The to-be-discriminated empty (silent) time intervals were marked by successive 20 ms stimuli, either auditory (5 ms rise and fall time) or visual. The auditory stimuli were 1 kHz pure tones generated by an IBM Pentium IV microcomputer running E-Prime software (version 1.1.4.1 – SP3). The computer was equipped with a Sound Blaster Audigy 2 sound card, and the tones were delivered binaurally through headphones (Sony MDR-V600) at an intensity of about 70 dB SPL. The visual stimuli were produced by a circular red-light-emitting diode (LED; Radio-Shack #276-088) placed about 1 m in front of the participant and subtending a visual angle of about 0.57 deg.

Each observer was seated in a dimly lit room and asked to respond, on each trial, whether the interval(s) of the second sequence of stimuli was (were) shorter or longer than the interval(s) of the first sequence of stimuli by pressing one of two labeled buttons on the computer keyboard.

2.3 *Procedure*

In each trial, participants experienced stimuli (tones or flashes) marking the intervals in the first sequence and stimuli (tones or flashes) marking the intervals in the second sequence and judged whether the intervals in the second sequence were shorter or longer than the intervals in the first. There was a 1 s pause between the offset of the last stimulus of the first sequence and the onset of the first stimulus of the second sequence.

For participants receiving the FV order, the first sequence marked a fixed 500 ms (standard) interval and the second sequence marked a variable (comparison) interval, while for those receiving the VF order, the variable intervals were presented in the first sequence. The variable intervals took on one of eight values: 395, 425, 455, 485, 515, 545, 575, and 605 ms.

Participants completed 8 experimental sessions, each lasting approximately 30 min. Within each session, the sequence condition (1 : 1, 1 : 4, 4 : 1, 4 : 4) was held constant and there were five 64-trial blocks (320 trials per session). Within each block, there were 8 presentations, in a random order, of each of the 8 comparison intervals. This results, for each participant, in 40 observations (8 repetitions $\times$ 5 blocks) per data point per sequence condition (ie per session). Within a session, there were 20 s between the blocks, and before the first session there were 8 practice trials.

The order of the four sequence conditions (1 : 1, 1 : 4, 4 : 1, 4 : 4) was balanced according to a Latin square with one participant assigned to each of four orders. Each participant completed two identical cycles of 4 sessions (8 sessions total with each sequence condition twice).

2.4 *Data analysis*

For each participant and session, an 8-point psychometric function was constructed, plotting the 8 variable intervals on the x-axis and the probability of responding "longer" on the y-axis. Each point on the psychometric function was based on 40 presentations.

A cumulative normal distribution function (CND) was fit to the resulting psychometric function. The CND was selected for tradition (Bonnet 1986) and convenience (Macmillan and Creelman 1991). Two indices of performance (parameters) were estimated, one for sensitivity and one for the perceived duration, with origin. As indicated in each section, the goodness-of-fit in the present study is generally very satisfactory.

As an indicator of temporal sensitivity, estimates of 1 SD on the psychometric function were determined. Using 1 SD (or variance) is a common procedure to express temporal sensitivity (Grondin 2005; Grondin et al 1999; Killeen and Weiss 1987). The other dependent variable was the point of subjective equality (PSE). The PSE can be defined as the x (duration) value corresponding to the 0.50 probability of "longer" responses on the y-axis. For each participant, the SD and PSE scores reported for the analysis were the average of the two estimates in each condition.

For each experiment, separate 2 (number of intervals in the first sequence: 1 or 4) $\times$ 2 (number of intervals in the second sequence: 1 or 4) ANOVAs were performed on SD and on PSE for the FV and VF order conditions.[1] Standard error bars reported in the figures were calculated by using the pooled error term from the ANOVA.

3 Experiment 1. Auditory – visual sequences

In experiment 1, the first sequence was marked by auditory stimuli and the second sequence was marked by visual stimuli.

3.1 *Participants*

Eight Laval University students, 20 to 47 years old (median age = 21.5 years), participated in experiment 1 of the study, four in FV order and four in VF order. They were paid Can $40 for their participation.

3.2 *Results*

3.2.1 *FV order.* Eight psychometric functions were constructed for each individual, two for each of the four experimental conditions. The goodness-of-fit was highly satisfactory. Out of 32 cases, 24 R^2 values were above 0.97 and 31 were above 0.94.

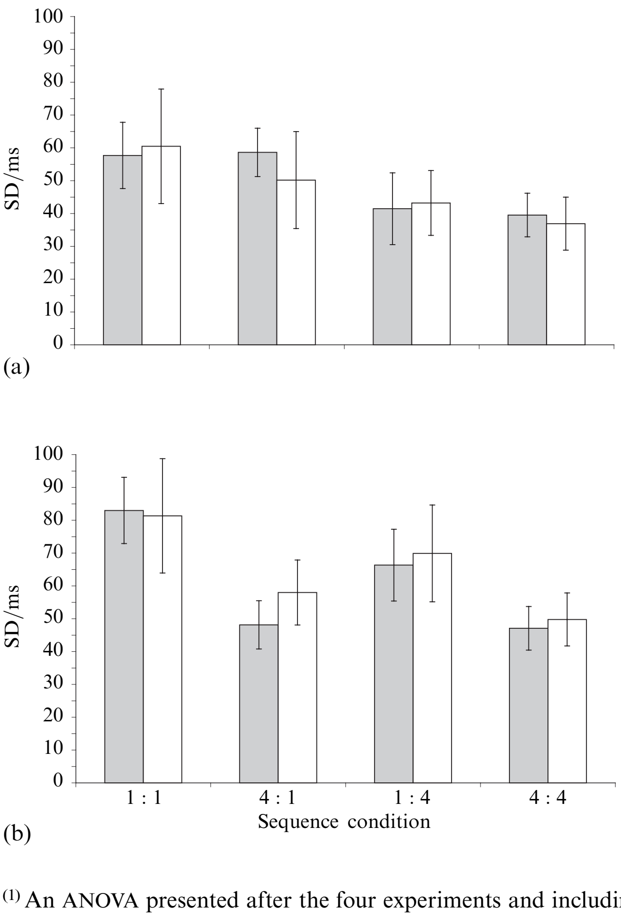

Figure 2. Average discrimination thresholds with standard error (SD) bars for the auditory – visual (AV) sequences examined in experiment 1 (shaded bars) and the visual – auditory (VA) sequences examined in experiment 2 (open bars): (a) FV order; (b) VF order.

[1] An ANOVA presented after the four experiments and including both FV and VF orders as a factor, and the four experiments as a factor, reveals that the number of intervals in the first sequence factor interacts with the order (FV versus VF), and there is also a significant number of intervals in the first sequence $\times$ number of intervals in the second sequence $\times$ experiment (modality condition) interaction effect. Therefore, for each experiment, we chose to present the results for each order individually.

Discrimination thresholds are summarized in table 1 and figure 2a (shaded bars). In general, figure 2a shows that discrimination performance was better when the second sequence involves 4 rather than only 1 interval. The ANOVA revealed a main effect of the number of intervals in the second sequence ($F_{1,3} = 11.44$, $p < 0.05$, $\eta^2 = 0.792$), but no main effect of the number of intervals in the first sequence and no interaction.

The PSE results are summarized in table 2. A PSE value larger than the standard value indicates that the visual intervals were perceived as shorter than the auditory intervals. The ANOVA revealed no significant main effects or interaction, although there was a marginal effect of the number of intervals in the second sequence ($p = 0.085$). The PSE is close to the 500 ms standard when 4 intervals are presented, but tends to be perceived as shorter than the 500 ms standard when only 1 visual interval is presented.

Table 1. Duration-discrimination thresholds for crossmodal and unimodal sequences presented in fixed – variable and variable – fixed order.

Sequence condition	Crossmodal duration comparisons				Unimodal duration comparisons			
	experiment 1, AV		experiment 2, VA		experiment 3, VV		experiment 4, AA	
	session 1	session 2	session 1	session 2	session 1	session 2	session 1	session 2
Fixed – variable								
1 : 1	55.39	60.00	60.99	59.97	70.88	61.40	36.55	31.32
4 : 1	55.36	61.89	57.59	42.78	83.94	58.53	33.46	26.04
1 : 4	48.90	34.00	47.18	39.27	48.95	51.05	27.96	25.46
4 : 4	43.67	35.38	31.60	42.22	34.91	35.54	18.85	22.25
Mean	50.83	47.82	49.34	46.06	59.67	51.63	29.20	26.27
Variable – fixed								
1 : 1	95.21	70.75	91.82	70.87	162.28	116.73	58.66	38.01
4 : 1	43.22	53.06	68.38	47.60	117.81	113.44	59.44	39.20
1 : 4	61.12	71.57	75.83	63.97	157.88	112.03	40.19	43.50
4 : 4	45.72	48.46	46.46	53.07	79.71	76.95	39.83	27.40
Mean	61.32	60.96	70.62	58.88	129.42	104.79	49.53	37.03

Table 2. Average PSE (ms) for crossmodal and unimodal sequences presented in fixed – variable and variable – fixed order.

Sequence condition	Crossmodal comparisons		Unimodal comparisons					
	experiment 1, AV		experiment 2, VA		experiment 3, VV		experiment 4, AA	
	session 1	session 2	session 1	session 2	session 1	session 2	session 1	session 2
Fixed – variable								
1 : 1	512.4	516.1	496.5	502.7	510.5	509.7	501.7	494.3
4 : 1	518.1	506.5	492.9	491.4	509.8	501.1	499.0	488.9
1 : 4	498.6	511.4	498.3	491.5	503.2	501.3	499.7	496.7
4 : 4	491.6	504.4	480.8	501.6	497.0	500.7	501.0	498.6
Mean	505.2	509.6	498.1	503.1	505.1	503.2	500.4	494.6
Variable – fixed								
1 : 1	502.5	489.2	495.3	502.4	492.3	476.5	487.6	496.3
4 : 1	505.0	497.8	510.0	509.7	501.7	491.7	481.1	485.7
1 : 4	495.9	480.2	496.6	499.5	475.0	455.9	489.5	494.6
4 : 4	496.6	498.2	490.5	500.6	512.2	492.7	499.5	503.2
Mean	500.0	491.3	492.1	496.8	495.3	479.2	489.4	495.0

3.2.2 *VF order.* Except for one participant who showed the three lowest R^2 values (0.78, 0.78, and 0.90), the goodness-of-fit was highly satisfactory. Out of 32 cases, 20 R^2 values were above 0.97 and 26 were above 0.94.

Discrimination thresholds are summarized in figure 2b (shaded bars). In general, figure 2b shows that discrimination performance seems better when the first (variable) sequence involves 4 rather than only 1 interval. The ANOVA revealed a main effect of the number of intervals in the first sequence ($F_{1,3} = 11.93$, $p < 0.05$, $\eta^2 = 0.799$), and marginally significant effects for the number of intervals in the second (fixed) sequence ($F_{1,3} = 6.90$, $p = 0.078$, $\eta^2 = 0.697$) and for the interaction ($F_{1,3} = 8.36$, $p = 0.063$, $\eta^2 = 0.736$).

The PSE results are also summarized in table 2. A PSE value smaller than the standard value indicates that the visual intervals were perceived as shorter than the auditory intervals. The ANOVA revealed no significant main effects or interaction.

3.2.3 *Summary.* This experiment revealed that, in the FV order, discrimination performance improved only when the number of intervals in the second (variable) sequence was increased. In the VF order, in contrast, discrimination performance improved when the number of intervals in the first (variable) sequence was increased, and to a lesser extent when the number of intervals in the second (fixed) sequence was increased. Thus, the number of intervals in the *variable* sequence (presented either first or second in the sequence pair) seems to be a key factor in determining discrimination performance. PSEs were relatively unaffected by order or number of sequence intervals. Moreover, goodness-of-fit estimates reveal greater stability in the FV condition than in the VF condition.

4 Experiment 2. Visual – auditory sequences

In experiment 2, the first sequence was marked by visual stimuli and the second sequence was marked by auditory stimuli.

4.1 *Participants*

Eight Laval University students, 20 to 50 years old (median age = 23 years), participated in this experiment, four in FV order and four in VF order. They were paid Can $40 for their participation. Three of them participated in experiment 1.

4.2 *Results*

4.2.1 *FV order.* As in experiment 1, the goodness-of-fit of the psychometric functions was highly satisfactory. Out of 32 cases, 23 R^2 values were above 0.97 and 28 were above 0.94.

Discrimination thresholds are summarized in figure 2a (open bars). In general, figure 2a shows that discrimination performance was better when the second sequence involves 4 rather than only 1 interval. The ANOVA revealed a main effect of the number of intervals in the second sequence ($F_{1,3} = 36.08$, $p < 0.01$, $\eta^2 = 0.923$), but there was no main effect of the number of intervals in the first sequence and no interaction effect.

The PSE results are summarized in table 2. A PSE value larger than the standard value indicates that the auditory intervals were perceived as shorter than the visual intervals. The ANOVA revealed no significant main effects or interaction.

4.2.2 *VF order.* The goodness-of-fit of the psychometric function was satisfactory but not as high as with the FV order. Out of 32 cases, 17 R^2 values were above 0.97 and 28 were above 0.94.

Discrimination thresholds are summarized in figure 2b (open bars). In general, figure 2b shows that discrimination performance was better when sequences involved 4 rather than only 1 interval. The ANOVA revealed a main effect of the number of intervals in the first sequence ($F_{1,3} = 11.88$, $p < 0.05$, $\eta^2 = 0.798$), but not a reliable main effect of the number of intervals in the second sequence (but note: $\eta^2 = 0.613$), nor a significant interaction.

The PSE results are summarized in table 2. A PSE value smaller than the standard value indicates that the auditory intervals were perceived as shorter than the visual intervals. The ANOVA revealed no significant main effects or interaction.

4.2.3 *Summary.* Using visual–auditory sequences in experiment 2 revealed essentially the same pattern of results as in experiment 1 with auditory–visual sequences. The number of intervals in the variable-sequence condition seems to be a more critical determinant of discrimination performance than the number of intervals in the fixed-sequence condition; however, in the VF order, the number of intervals in the second (fixed) sequence has a non-negligible effect on thresholds in both experiments 1 and 2. Once again, there is no significant effect on PSEs.

5 Experiment 3. Visual – visual sequences

In experiment 3, the first and second sequences were both visual.

5.1 *Participants*

Eight Laval University students, 20 to 51 years old (median age = 22 years), participated in experiment 3, four in FV order and four in VF order. They were paid Can $40 for their participation. One of them participated in experiments 1 and 2 and two others participated in experiment 2.

5.2 *Results*

5.2.1 *FV order.* The goodness-of-fits were high. Out of 32 cases, 26 R^2 values were above 0.97 and all were above 0.94.

Discrimination thresholds are summarized in figure 3a (shaded bars). In general, figure 3a shows that discrimination performance was better when the second sequence involved 4 rather than only 1 interval. In the ANOVA, there was only a marginally significant effect of the number of intervals in the second sequence ($F_{1,3} = 8.91$, $p < 0.058$, $\eta^2 = 0.748$); there were no other main effects or interactions.

The PSE results are summarized in table 2. A PSE value larger than the standard value indicates that the intervals in the second sequence were perceived as shorter than the intervals of the first sequence. The ANOVA revealed no significant main effects or interaction.

5.2.2 *VF order.* The goodness-of-fits were satisfactory, but not as high as in experiments 1 and 2, or as with the FV order. Out of 32 cases, there were 13 R^2 values below 0.90, including 5 by each of two participants. Nevertheless, 10 R^2 values were above 0.97 and 15 were above 0.94.

Discrimination thresholds are summarized in figure 3b (shaded bars). The ANOVA revealed no significant effects; however, effect size estimates for the number of intervals in the first sequence factor, the number of intervals in the second sequence factor, and the interaction terms were $\eta^2 = 0.570$, 0.643, and 0.462, respectively.

The PSE results are summarized in table 2. A PSE value smaller than the standard value indicates that the intervals in the second sequence were perceived as shorter than the intervals of the first sequence. The ANOVA revealed no significant main effects, the interaction effect was marginally significant ($F_{1,3} = 8.63$, $p = 0.061$, $\eta^2 = 0.742$). When there are 4 intervals in the second sequence and only 1 in the first, the latter (only 1 interval) tends to be perceived as longer.

5.2.3 *Summary.* The pattern of results for visual–visual sequences was similar, but not identical to that found for the two crossmodal sequence conditions. In the FV order, the number of intervals in the second (variable) sequence influenced discrimination

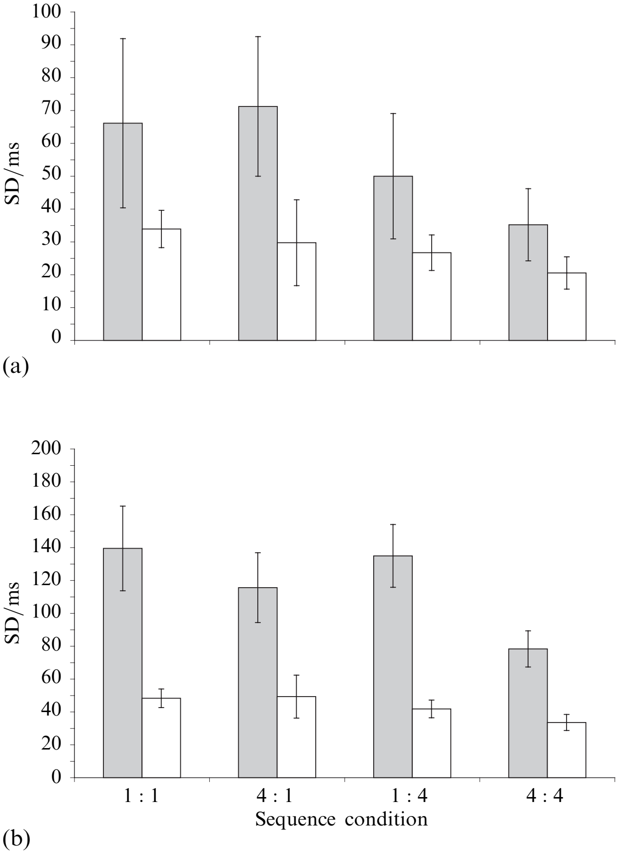

Figure 3. Average discrimination thresholds with standard error (SD) bars for the visual – visual (VV) sequences examined in experiment 3 (shaded bars) and for the auditory – auditory (AA) sequences examined in experiment 4 (open bars): (a) FV order; (b) VF order.

performance, but not the number of intervals in the first (fixed) sequence. In the VF order, the pattern or the data mirrored those found for crossmodal sequence conditions in experiments 1 and 2, but none of the effects was significant. This greater ambiguity may have reflected the overall poorer goodness-of-fit estimates of the individual psychometric functions.

6 Experiment 4. Auditory – auditory sequences

In experiment 4, the first and second sequences were both auditory.

6.1 *Participants*

Eight Laval University students, 20 to 33 years old (median age = 23 years), participated in experiment 4, four in FV order and four in VF order. They were paid Can $40 for their participation. None of them participated in experiments 1 – 3.

6.2 *Results*

6.2.1 *FV order.* The goodness-of-fit was very high in each condition with all 32 R^2 values above 0.97.

Discrimination thresholds are summarized in figure 3a (open bars). In general, figure 3a shows that discrimination performance was better when the first or second sequence involved 4 rather than only 1 interval. The ANOVA revealed a main effect of the number of intervals in the first sequence ($F_{1,3} = 18.29$, $p < 0.05$, $\eta^2 = 0.859$), but the main effect of the number of intervals in the second sequence was not significant ($F_{1,3} = 5.44$, $p = 0.10$, $\eta^2 = 0.644$). The interaction effect was not significant.

The PSE results are summarized in table 2. PSE values larger than the standard value indicate that the intervals in the second sequence were perceived as shorter than the intervals of the first sequence. The ANOVA revealed no significant main effects or interaction.

6.2.2 *VF order.* As with the FV order, the goodness-of-fit was highly satisfactory in each condition. Out of 32 cases, 28 R^2 values were above 0.97 and all were above 0.94.

Discrimination thresholds are summarized in figure 3b (open bars). The ANOVA revealed no significant main effects, but there was a marginally significant effect of the number of intervals in the second sequence ($F_{1,3} = 5.82$, $p = 0.095$, $\eta^2 = 0.660$).

The PSE results are summarized in table 2. The ANOVA revealed no significant main effects, but the interaction effect was significant ($F_{1,3} = 13.65$, $p < 0.05$, $\eta^2 = 0.820$). When there are 4 intervals in the second sequence and only 1 in the first, the former tend to be perceived as longer.

6.2.3 *Summary.* Auditory – auditory sequences produced much lower thresholds (better discrimination performance) than visual – visual sequences; moreover, unlike in the previous studies, the goodness-of-fit values were quite high for both the FV and VF orders. Overall pattern of results differed somewhat from the previous three experiments. Somewhat surprising was the finding that the number of intervals in the fixed sequence, presented first in the FV order and second in the VF order, had the greatest effect on discrimination performance.

6.2.4 *Combined analysis.* In order to compare the results across the set of experiments, the different modality conditions (experiments 1 – 4) and the order conditions (FV versus VF), we conducted an additional ANOVA according to a 2 (1 versus 4 intervals in the first sequence) × 2 (1 versus 4 intervals in the second sequence) × 2 (orders) × 4 (modality condition) design, with repeated measures on the first two factors only.(2)

Across the experiments, the ANOVA revealed a main effect of the number of intervals in the first sequence ($F_{1,24} = 17.05$, $p < 0.001$, $\eta^2 = 0.415$); a main effect of the number of intervals in the second sequence ($F_{1,24} = 56.98$, $p < 0.001$, $\eta^2 = 0.704$); a main effect of order ($F_{1,24} = 9.98$, $p < 0.01$, $\eta^2 = 0.294$); and a main effect of modality ($F_{3,24} = 6.28$, $p < 0.001$, $\eta^2 = 0.440$). In general, sensitivity was higher (SD lower) in the FV than in the VF condition, and when both sequences were auditory rather than visual; thresholds for the two crossmodal timing conditions were intermediate compared to the two unimodal conditions. In addition to the main effects, there are two significant interaction effects: number of intervals in the first sequence × order ($F_{1,24} = 7.48$, $p < 0.05$, $\eta^2 = 0.238$), and number of intervals in the first sequence × number of intervals in the second sequence × modality interaction ($F_{3,24} = 3.39$, $p < 0.05$, $\eta^2 = 0.298$).

The interaction with the order factor shows that increasing the number of intervals in the first sequence is much more important in the VF order than in the FV order, whereas the number of intervals in the second sequence is more important in the FV order than in the VF order (see McAuley and Miller 2007 and Miller and McAuley 2005 for a similar pattern of results for auditory – auditory sequences only). The number of intervals in the first sequence × the number of intervals in the second sequence × modality interaction is due to the fact that, when there is only one interval in the second sequence, the benefits gained by increasing the number of intervals in the first sequence is strong in experiments 1 – 3, but weak when only auditory markers are used (experiment 4).

(2) While it is clear that different participants completed the FV and VF orders in each experiment, some subjects participated in more than one experiment. Nevertheless, for simplicity, and because there was more than 1 month between experiments, we opted to consider the between-experiments (modality conditions) factor a between-subjects factor.

7 General discussion

Four experiments extended previous work on the multiple-interval advantage to crossmodal timing conditions. In all experiments, participants experienced sequence pairs, each consisting of 1 or 4 time intervals (marked by 2 or 5 brief stimuli—tones or flashes), and were asked to indicate whether the time intervals marked by the second sequence were shorter or longer than the intervals marked by the first sequence. The aims of this research were threefold. First, we were interested in determining if there is a multiple-interval advantage in crossmodal timing conditions, and in comparing crossmodal timing performance to equivalent unimodal conditions. Second, given the presence of a multiple-interval advantage, we were interested in measuring the relative contribution of number of intervals in the first and second sequence (marked by auditory or visual signals) to overall discrimination performance. Finally, we were interested in assessing the order issue (FV versus VF) in the context of the crossmodal and multiple-interval conditions. Here we will focus on these issues.

7.1 *Crossmodal versus unimodal duration comparisons*

In experiments 1 and 2 we examined auditory – visual and visual – auditory sequence pairings, respectively, and found that overall duration discrimination improved when there were more intervals in either the first (auditory or visual) sequence or the second (visual or auditory) sequence (ie there was a crossmodal multiple-interval advantage). However, improvements associated with increasing the number of sequence intervals were mediated by order (FV versus VF). In both experiments 1 and 2, increasing the number of intervals in the second sequence had a larger effect on thresholds in the FV order than in the VF order, while, conversely, increasing the number of intervals in the first sequence tended to have a larger effect on thresholds in the VF order than in the FV order. This order effect is consistent with that reported by Miller and McAuley (2007) for auditory – auditory sequence pairings. Overall, the results from experiments 1 and 2 are important because they are the first to show a multiple-interval advantage in crossmodal timing conditions. The comparison across the two experiments is important because it shows that the crossmodal multiple-interval advantage does not depend on the specific modalities (auditory or visual) assigned to the two sequences.

In experiments 3 and 4 we used the same procedure, but examined unimodal timing conditions; participants were presented with only visual sequences (experiment 3) or auditory sequences (experiment 4). Similar to the crossmodal timing conditions of experiments 1 and 2, increasing the number of intervals in either the first sequence or the second sequence tended to improve discrimination performance, but the effect was larger when the intervals were presented in the second sequence in the FV condition. Moreover, best performance was observed when both sequences contained 4 intervals; this finding applied to both the FV and VF orders. The results were not as clear in experiment 3 (visual – visual sequences) as the overall performance was much lower than in the other three experiments.

Across the four experiments, the results revealed that duration-discrimination performance is most accurate with auditory – auditory sequences (experiment 4), worst with the visual – visual sequences (experiment 3), and intermediate (and very similar) with auditory – visual and visual – auditory sequences (experiments 1 and 2). The comparison of unimodal conditions in experiments 3 and 4 contributes to a growing body of work demonstrating that duration discrimination is better with auditory markers than with visual ones. This result is consistent with previous findings on this issue (Grondin et al 2001, 2004, 2005; Penney et al 2000). In the present study, we extended this result to sequence conditions, involving different combinations of multiple-interval presentations. Moreover, the data of experiments 1 and 2 are also an occasion to compare the relative efficiency of crossmodal sequence comparisons (visual – auditory versus auditory–visual). The general picture that emerges is that there is not much difference between the auditory–visual and visual–auditory sequences. This finding differs slightly from that of Ulrich et al (2006) who observed for standard ranging from 100 ms to 1000 ms, in conditions where the first stimulus is the standard (FV order), that discrimination thresholds were higher with a visual–visual sequence than with a visual–auditory sequence, but not higher than with an auditory–visual sequence. In other words, in their experiments, having the comparison interval presented in the auditory mode seems to have improved performance. One notable methodological difference, however, is that the Ulrich et al study involved filled intervals, whereas the present study involved empty intervals.

In the reported experiments, findings involving unimodal versus crossmodal conditions contrast with other data on the discrimination of intervals marked by intramodal versus intermodal signals (see Grondin 2003). In these experiments, it is the single stimulus mode of interval presentation that is mostly used and in each trial, an empty interval is presented (empty duration between two brief sensory signals). When the intervals are marked by signals delivered from different sensory modes, either a visual–auditory or an auditory–visual sequence pairing produces worse discrimination performance than when both signals are delivered from the same sensory mode, either auditory or visual (Grondin and Rousseau 1991; Grondin et al 2005; Rousseau et al 1983). However, these data are consistent with those of van Erp and Werkhoven (2004) who reported that the discrimination levels remain the same when tactile–tactile, visual–visual, tactile–visual, or visual–tactile intervals are compared.

7.2 *Locus of the multiple-interval advantage*

The current work contributes to research on the multiple-interval advantage, namely that when two time intervals of different duration have to be discriminated, multiple presentations of these intervals within a sequence improves temporal discrimination (Drake and Botte 1993; Grondin 2001a; McAuley and Kidd 1998; McAuley and Miller 2007; Miller and McAuley 2005). In studies that have demonstrated a multiple-interval advantage, the first sequence typically specifies a fixed (standard) interval, while the second sequence specifies a variable (comparison) interval. In these instances, the multiple-interval advantage has often been explained by using a multiple-look hypothesis (Drake and Botte 1993), in which multiple presentations of the standard interval in the first sequence are assumed to improve the precision of the representation in memory of the standard interval value.

Recent research, however, has revealed that, at least in some cases, the impact of the number of intervals in the first (standard) sequence is very limited and rather it is the number of intervals in the second (comparison) sequence that is the critical factor (McAuley and Miller 2007; Miller and McAuley 2005). The present study generalizes this finding to crossmodal timing conditions (experiments 1 and 2) and visual–visual sequence pairings (experiment 3). A generalized version of the multiple-look model was developed by Miller and McAuley (2005) to account for the impact of the multiple presentations of the comparison/variable intervals in the second sequence.

In the generalized multiple-look (GML) model, the original multiple-look model of Drake and Botte (1993) is extended to measure average sampling error for two independent samples, as shown below:

$$\mathrm{SD}_{n_1:n_2} = \sqrt{\frac{w(\mathrm{SD}_{1:1})^2}{n_1} + \frac{(1-w)(\mathrm{SD}_{1:1})^2}{n_2}}\,. \tag{2}$$

The model has two additive terms; the first term models the contribution of the first sequence (fixed standard) and the second term models the contribution of the second sequence (variable comparison), with n_1 and n_2 specifying the number of intervals in each sequence, respectively. Consistent with Drake and Botte, thresholds (denoted here as $SD_{n_1:n_2}$ for isochronous n_1-interval and n_2-interval comparison sequences) are based on the observed SD for the single-interval case ($SD_{1:1}$) and thresholds are similarly predicted to have an inverse relationship with the number of sequence intervals. However, the relative contribution of the number of intervals in the first and second sequences to thresholds is permitted to vary by using a relative-weight parameter w.

Descriptive application of the GML model (see equation 2) is useful for highlighting the main findings in the present study. Specifically, best-fitting estimates of w provide a quantitative interpretation of the relative contribution of the number of intervals in the first sequence to duration-discrimination performance in crossmodal and unimodal sequence conditions for the FV and VF orders. In this model, values of w greater than 0.5 indicate that the number of intervals in the first sequence provides a greater contribution to thresholds than the number of intervals in the second sequence. The results of the fits of the GML model to the data of experiments 1 – 4 are shown in table 3. Consistent with the observation that it is the number of variable (comparison) intervals that matters, estimated values of w are much smaller in the FV order than those obtained for the VF order. This is independent of marker modality and whether the duration comparisons are crossmodal or unimodal; the lone exception is the auditory – auditory sequences examined in experiment 4. Moreover, the GML model fits the data quite well for the FV order across the different modality conditions. However, the model is somewhat less successful in fitting the results observed in the VF order.

Table 3. Estimated values of w obtained from fits of the GML model to the data from experiments 1 – 4; values of w greater than 0.5 indicate that thresholds are determined more by the number of intervals in the first sequence than in the second sequence, whereas values less than 0.5 indicate the opposite.

Comparisons	FV order	VF order
Crossmodal		
Experiment 1, AV	0.22	0.76
Experiment 2, VA	0.38	0.65
Experiments 1 and 2 combined	0.30	0.71
Unimodal		
Experiment 3, VV	0.22	0.63
Experiment 4, AA	0.41	0.36
Experiments 3 and 4 combined	0.31	0.50
Experiments 1 – 4 combined	0.31	0.60

Indeed, for both crossmodal comparisons (experiments 1 and 2) and in unimodal comparison of visual sequences (experiment 3), increasing the number of repetitions of the variable interval generally reduced temporal discrimination thresholds, independently of whether the variable interval was presented second (FV order) or first (VF order) within the sequence pair. In the FV order, increasing the number of intervals in the second sequence resulted in better discrimination, while in the VF order, increasing the number of intervals in the first sequence improved performance. In other words, in these experiments, it is the number of *variable* intervals that seems to be the crucial factor.

7.3 *Effect of order*

The results of experiments 1 – 4 also revealed that, overall, duration discrimination was systematically better in the FV order than in the VF order, with one exception: auditory – visual sequences in the 4 : 1 condition. Some insight about this difference is revealed by Lapid et al (2008), who also found an order effect in their examination of duration-discrimination thresholds for single intervals presented using the reminder procedure (standard always presented first) compared to the 2-alternative forced-choice procedure (2AFC) where the position of the standard is variable from trial to trial (roving standard). These authors consistently observed better discrimination in the reminder condition, where the first sequence presented a fixed standard interval. These findings and others suggest that when the first interval is fixed on every trial, individuals have the potential to develop a long-term reference for the standard interval (see also Miller and McAuley 2005).

Further support for this interpretation comes from the visual-perception literature, which has revealed that presenting or not presenting a standard – comparison (or FV) interval pair in each experimental trial does not necessarily lead to better duration-discrimination performance than presenting only a single (comparison) stimulus on each trial (Morgan et al 2000; Nachmias 2006). With the single-stimulus method in particular, participants make judgments about the duration of an isolated comparison stimulus in relation to an absent long-term temporal referent (Allan 1979; Grondin 1993, 2005; Grondin et al 1999).

More generally, there is increasing evidence that the perceived duration of time intervals marked by stimulus sequences is influenced by the extended temporal context of those judgments (Jones and McAuley 2005; McAuley and Jones 2003). Jones and McAuley (2005) had participants make duration judgments about standard – comparison sequences marked by tones, while manipulating the mean, range, standard deviation, and number of different standard time intervals within a testing session. They found that memory for a standard time interval was influenced by at least three factors: the global distributional properties of a session (eg mean and range of intervals), trial-to-trial contingencies, and the standard interval itself.

One processing-based explanation that has the potential to account for the effect of FV versus VF order difference is reported by Lapid et al (2008). This approach shared conceptual features with entrainment approaches to timing in which individuals pick up on (attune to) an implied beat that they used then to gauge relative judgments about sequence timing (Large and Jones 1999; McAuley 1995; McAuley and Jones 2003). In the Lapid et al proposal, the representation of the internal standard, I, used as the referent for duration comparisons, is based on the weighted combination, g, of information coming from previous trials, A (a moving average), and from the representation of the interval(s) presented first, X_1, in a given trial:

$$I = gA + (1 - g)X_1 ,$$

where $0 < g < 1$. In a given trial, it is then the second interval, X_2, that is compared to the updated standard value, I. From the perspective of this model, when the variable (comparison) interval(s) are delineated by the first sequence (as X_1), that is going to yield a less stable representation of the long-term referent, and hence worse discrimination performance than when variable (comparison) interval(s) are marked by the second sequence (as X_2). Thus, the multiple presentations of these comparison values would either increase the variance of I when presented first, or reduce its share of variance when presented second.

7.4 *Conclusions and further studies*

The current study reveals a multiple-interval advantage in crossmodal sequence conditions that is similar to that found for unimodal conditions. Overall duration discrimination improves when there are more intervals in either the first sequence or the second sequence, independent of modality. However, the results are mediated by whether the time intervals marked by the first sequence or second sequence are fixed or variable from trial to trial. Consistent with Miller and McAuley (2005), increasing the number of intervals has a larger effect on thresholds when the intervals marked by the sequence are variable, independently of whether the variable intervals are in the first or second sequence. Finally, a comparison across conditions shows that crossmodal conditions yield thresholds that are intermediate to those for auditory–auditory and visual–visual sequence conditions. This last finding supports an auditory dominance view of temporal processing; it matters more that one of the sequences is auditory than whether the modality of the two sequences is the same.

These findings still need to be generalized in two ways. On the one hand, because there are evidences in the literature on auditory duration discrimination that there is a fundamental difference between fast sequences (empty intervals < 250 ms) and slower sequences (empty intervals > 250 ms) (eg Friberg and Sundberg 1995; ten Hoopen et al 1994), the present demonstration should be extended to briefer intervals. Given the results reported by ten Hoopen et al (2004), it is likely that the same multiple-interval advantage would be observed. On the other hand, restricting the demonstration to 1 and 4 intervals as in the present study is a bit limited. As concisely described by ten Hoopen et al (2004), a more complete demonstration would involve many multiple-interval conditions, which would allow a more precise quantitative description of the relationship between the discrimination performances and the number of intervals involved.

Acknowledgments. This research was made possible by a research grant awarded to SG by the Natural Sciences and Engineering Council of Canada (NSERC) and by grants from the National Institutes of Health and the GRAMMY foundation awarded to JDM. We would like to express our gratitude to Marilyn Plourde and Nicolas Bisson, who provided precious help at various stages of the project and to Molly Henry, Nathan Miller, Ann Mary Mercier, and Louis Vinke for their comments on a draft of this manuscript. We would also like to express specials thanks to Gert ten Hoopen and one anonymous reviewer for their careful reading of a previous version of the article and for their detailed comments. This study was presented at the 48th Annual Meeting of the Psychonomic Society held in Long Beach, CA, in 2007.

References

Allan L G, 1979 "The perception of time" *Perception & Psychophysics* **26** 340–354

Bahrick L E, Lickliter R, 2000 "Intersensory redundancy guides attentional selectivity and perceptual learning in infancy" *Developmental Psychology* **36** 190–200

Bahrick L E, Lickliter R, Flom R, 2004 "Intersensory redundancy guides infants' selective attention, perceptual, and cognitive development" *Current Directions in Psychological Science* **13** 99–102

Bonnet C, 1986 *Manuel pratique de psychophysique* (Paris: Armand Colin)

Church R M, 1984 "Properties of the internal clock", in *Annals of the New York Academy of Sciences* volume 423 *Timing and Time Perception* Eds J Gibbon, L G Allan (New York: New York Academy of Sciences) pp 566–582

Creelman C D, 1962 "Human discrimination of auditory duration" *Journal of the Acoustical Society of America* **34** 582–593

Drake C, Botte M-C, 1993 "Tempo sensitivity in auditory sequences: Evidence for a multiple-look model" *Perception & Psychophysics* **54** 277–286

Erp J B F van, Werkhoven P J, 2004 "Vibro-tactile and visual asynchronies: Sensitivity and consistency" *Perception* **33** 103–111

Friberg A, Sundberg J, 1995 "Time discrimination in a monotonic, isochronic sequence" *Journal of the Acoustical Society of America* **98** 2524–2531

Gibbon J, Church R M, 1984 "Sources of variance in an information processing theory of timing", in *Animal Cognition* Eds H L Roitblat, T G Bever, H S Terrace (Hillsdale, NJ: Lawrence Erlbaum Associates) pp 465–488

Gibbon J, Church R M, Meck W H, 1984 "Scalar timing in memory", in *Annals of the New York Academy of Sciences* volume 423 *Timing and Time Perception* Eds J Gibbon, L G Allan (New York: New York Academy of Sciences) pp 52–77

Grondin S, 1993 "Duration discrimination of empty and filled intervals marked by auditory and visual signals" *Perception & Psychophysics* **54** 383–394

Grondin S, 2001a "Discriminating time intervals presented in sequences marked by visual signals" *Perception & Psychophysics* **63** 1214–1228

Grondin S, 2001b "From physical time to the first and second moments of psychological time" *Psychological Bulletin* **127** 22 – 44
Grondin S, 2003 "Sensory modalities and temporal processing", in *Time and Mind 02* Ed. H Helfrich (Göttingen: Hogrefe & Huber) pp 75 – 92
Grondin S, 2005 "Overloading temporal memory" *Journal of Experimental Psychology: Human Perception and Performance* **31** 869 – 879
Grondin S, 2008 "Methods for studying psychological time", in *Psychology of Time* Ed. S Grondin (Bingley, UK: Emerald Group Publishing) pp 51 – 74
Grondin S, Girard C, 2005 "About hemispheric differences in the processing of temporal intervals" *Brain and Cognition* **58** 125 – 132
Grondin S, Meilleur-Wells G, Lachance R, 1999 "When to start explicit counting in a time-intervals discrimination task: A critical point in the timing process by humans" *Journal of Experimental Psychology: Human Perception and Performance* **25** 993 – 1004
Grondin S, Ouellet B, Roussell M-E, 2001 "About optimal timing and stability of Weber fraction for duration discrimination" *Acoustical Science & Technology* **22** 370 – 372
Grondin S, Ouellet B, Roussel M-E, 2004 "Benefits and limits of explicit counting for discriminating temporal intervals" *Canadian Journal of Experimental Psychology* **58** 1 – 12
Grondin S, Rousseau R, 1991 "Judging the relative duration of multimodal short empty time intervals" *Perception & Psychophysics* **49** 245 – 256
Grondin S, Roussel M-E, Gamache P-L, Roy M, Ouellet B, 2005 "The structure of sensory events and the accuracy of time judgments" *Perception* **34** 45 – 58
Hoopen G ten, Akerboom S, 1983 "The subjective tempo difference between interaural and monaural sequences as a function of sequence length" *Perception & Psychophysics* **34** 465 – 469
Hoopen G ten, Berg S van den, Memelink J, Bocanegra B, Boon R, 2004 "Multiple looks on temporal discrimination in sound sequences" *Transactions of Technical Committee of Psychological and Physiological Acoustics—The Acoustical Society of Japan* **34** 693 – 700
Hoopen G ten, Boelaarts L, Gruisen A, Apon I, Donders K, Mul N, Akerboom S, 1994 "The detection of anisochrony in monaural and interaural sequences" *Perception & Psychophysics* **56** 110 – 120
Hoopen G ten, Hartsuiker R, Sasaki T, Nakajima Y, Tanaka M, Tsumura T, 1995 "Auditory isochrony: Time shrinking and temporal patterns" *Perception* **24** 577 – 593
Ivry R B, Hazeltine R E, 1995 "The perception and production of temporal intervals across a range of durations: Evidence for a common timing mechanism" *Journal of Experimental Psychology: Human Perception and Performance* **21** 3 – 18
Jones M R, McAuley J D, 2005 "Time judgments in global temporal contexts" *Perception & Psychophysics* **67** 398 – 417
Keele S W, Nicoletti R, Ivry R, Pokorny R A, 1989 "Mechanisms of perceptual timing: Beat-based or interval-based judgements?" *Psychological Research* **50** 251 – 256
Killeen P R, Weiss N A, 1987 "Optimal timing and the Weber function" *Psychological Review* **94** 455 – 468
Lapid E, Ulrich R, Rammsayer T H, 2008 "On estimating the difference limen in temporal-discrimination tasks: A comparison of the 2AFC and the reminder tasks" *Perception & Psychophysics* **70** 291 – 305
Large E W, Jones M R, 1999 "The dynamics of attending: How we track time varying events" *Psychological Review* **106** 119 – 159
McAuley J D, 1995 *Perception of Time as Phase: Toward an Adaptive Oscillator Model of Rhythmic Pattern Processing* unpublished dissertation, Indiana University, Bloomington, IN, USA
McAuley J D, Jones M R, 2003 "Modeling effects of rhythmic context on perceived duration: A comparison of interval and entrainment approaches to short-interval timing" *Journal of Experimental Psychology: Human Perception and Performance* **29** 1102 – 1125
McAuley J D, Kidd G R, 1998 "Effect of deviations from temporal expectations on tempo discrimination of isochronous tone sequences" *Journal of Experimental Psychology: Human Perception and Performance* **24** 1786 – 1800
McAuley J D, Miller N, 2007 "Picking up the pace: Effects of global temporal context on sensitivity to the tempo of auditory sequences" *Perception & Psychophysics* **69** 709
Macmillan N A, Creelman C D, 1991 *Detection Theory: A User's Guide* (New York: Cambridge University Press)
Meck W H (Ed.), 2003 *Functional and Neural Mechanisms of Interval Timing* (Boca Raton, FL: CRC Press)
Michon J A, 1964 "Studies of subjective duration I" *Acta Psychologica* **22** 441 – 450

Miller N, McAuley J D, 2005 "Tempo sensitivity in isochronous tone sequences: The multiple-look model revisited" *Perception & Psychophysics* **67** 1150 – 1160

Morgan M J, Watamaniuk S N J, McKee S P, 2000 "The use of an implicit standard for measuring discrimination thresholds" *Vision Research* **40** 2341 – 2349

Nachmias J, 2006 "The role of visual standard in visual discrimination" *Vision Research* **46** 2456 – 2464

Pashler H, 2001 "Perception and production of brief durations: Beat-based versus interval-based timing" *Journal of Experimental Psychology: Human Perception and Performance* **27** 485 – 493

Penney T B, Gibbon J, Meck W H, 2000 "Differential effects of auditory and visual signals on clock speed and temporal memory" *Journal of Experimental Psychology: Human Perception and Performance* **26** 1770 – 1787

Pfeuty M, Ragot R, Pouthas V, 2003 "When time is up: CNV time course differentiates the roles of the hemispheres in the discrimination of short tone durations" *Experimental Brain Research* **151** 372 – 379

Pouthas V, Macar F, 2005 "Les bases neuronales de la perception du temps et de la régulation temporelle de l'action" *Psychologie Française* **50** 27 – 45

Roeckelein J, 2008 "History of conceptions and accounts of time and early time perception research", in *Psychology of Time* Ed. S Grondin (Bingley, UK: Emerald Group Publishing) pp 1 – 50

Rousseau L, Rousseau R, 1996 "Stop-reaction time and the internal clock" *Perception & Psychophysics* **58** 434 – 448

Rousseau R, Poirier J, Lemyre L, 1983 "Duration discrimination of empty time intervals marked by intermodal pulses" *Perception & Psychophysics* **34** 541 – 548

Treisman M, 1963 "Temporal discrimination and the indifference interval: Implications for a model of the 'internal block'" *Psychological Monographs* **77** 1 – 31

Ulrich R, Nitschke J, Rammsayer T, 2006 "Crossmodal temporal discrimination: Assessing the predictions of a general pacemaker-counter model" *Perception & Psychophysics* **68** 1140 – 1152

Woodrow H, 1951 "Time perception", in *Handbook of Experimental Psychology* Ed. S S Stevens (New York: John Wiley & Sons) pp 1224 – 1236

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 38 2009

www.perceptionweb.com