Acta Psychologica 156 (2015) 83–95

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

How are overlapping time intervals perceived? Evidence for a weighted sum of segments model

Donna Bryce *, Tanja Seifried-Dübon, Daniel Bratzke

Department of Psychology, University of Tübingen, Schleichstrasse 4, 72072 Tübingen, Germany

ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form 16 December 2014
Accepted 18 December 2014
Available online 20 February 2015

PsychInfo code:
2320 Sensory Perception

Keywords:
Time perception
Reproduction
Overlapping intervals
Unimodal
Bimodal
Pacemaker accumulator models

ABSTRACT

This study investigated the way in which people time two overlapping intervals. Timing models already proposed in the literature predict different effects of the degree of overlap on each estimate, and empirical findings were compared to these predictions. Two unimodal experiments (in which each to-be-timed interval was a visual stimulus) and one bimodal experiment (in which one to-be-timed interval was auditory and the other visual) were conducted. The estimate of the first interval was either unaffected or decreased, and the estimate of the second interval consistently increased as the intervals were more temporally separated. The only model in the literature that could account for such result patterns is a single pacemaker single accumulator structure with an additional recency weighting (see the *weighted sum of segments* model). That is, participants appear to segment the two overlapping intervals into three non-overlapping and overlapping segments, time these segments separately, and then combine them to estimate each interval. Importantly, a recency weighting, determined by the time that has passed since the end of that segment, is also applied to each segment in the summation process. Further, in the bimodal experiment the order in which the stimuli of different modalities were presented affected the way in which they were timed, a finding that none of the current models can explain. This highlights that a comprehensive model of interval timing must consider not only the modalities of to-be-timed intervals but also the order in which different modalities must be timed.

1. Introduction

How people perceive short intervals of time and then recreate these intervals or compare them to other short intervals has been the focus of research for many years (François, 1927; Hoagland, 1933). This type of timing is called prospective interval timing, because the participants know in advance that they should attend to time. The most commonly used cognitive models of prospective interval timing are pacemaker-accumulator models (Church, 1984; Creelman, 1962; Rammsayer & Ulrich, 2001; Treisman, 1963; Zakay & Block, 1997). These models posit that an internal pacemaker emits pulses which pass through a switch and are stored by an accumulator. The number of pulses can be stored for a short time in working memory, or for a longer time in reference memory, to facilitate comparisons. The rate at which these pulses are emitted is debated (van Rijn & Taatgen, 2008; Wearden & Jones, 2007); it could be constant (i.e. the gaps between pulses are always the same, producing a linear timescale), or the rate of pulses could decrease with real time (i.e. the gaps between pulses increase, resulting in a nonlinear timescale). According to these models, in order to reproduce a previously perceived interval, the participant simply ceases the reproduction when the same number of pulses has been accumulated as were perceived. In order to compare two intervals, the number of pulses in working memory is compared to the number of pulses collected in relation to the second interval.

Simple interval timing can be achieved in a fairly straightforward manner using the pacemaker-accumulator model. However, what is less well understood is how people time intervals that overlap. Such intervals could in fact be more representative of the timing that people require in everyday situations. This skill could be particularly important, for instance, in order to judge one's own performance in a multi-tasking situation where the processing of two tasks overlaps (Bryce & Bratzke, 2014; Corallo, Sackur, Dehaene, & Sigman, 2008; Marti, Sackur, Sigman, & Dehaene, 2010). There is some evidence from animal studies for the existence of different pacemakers that are used for intervals of different durations (Buhusi & Meck, 2005). However, even if it is possible for humans to use more than one pacemaker and accumulator, it remains unknown exactly how participants behave in a multiple timing context. Certainly, the few studies that have directly investigated multiple timing in humans have shown it to be an effortful process that leads to deterioration in timing performance (Brown, Stubbs, & West, 1992; Brown & West, 1990; Gamache & Grondin, 2010; Grondin, 2010).

Most multiple timing studies have considered the effects of increasing the number of to-be-timed intervals, rather than the degree

* Corresponding author at: Fachbereich Psychologie, Universität Tübingen, Schleichstrasse 4, 72072 Tübingen, Germany. Tel.: +49 7071 29 76762; fax: +49 7071 29 2410.
E-mail addresses: donna.bryce@uni-tuebingen.de (D. Bryce), tanja.gb@gmx.de (T. Seifried-Dübon), daniel.bratzke@uni-tuebingen.de (D. Bratzke).

http://dx.doi.org/10.1016/j.actpsy.2014.12.007
0001-6918/

of simultaneity of two intervals. One previous study (van Rijn & Taatgen, 2008) has addressed the simultaneity issue by examining how accurately people produce pre-learned intervals when they overlap with one another. That is, participants learned to produce specific intervals (2 or 3 s), and then had to indicate when that period of time had elapsed after two separate start signals. There was a stimulus onset asynchrony (SOA) between the two start signals that resulted in the two intervals overlapping by varying degrees. van Rijn and Taatgen (2008) found that as the two intervals became more temporally separated (i.e. SOA increased), participants' estimates of the second interval increased, whereas the estimate of the first interval was unchanged. Further, they found that the two estimates were not independent. That is, on a trial-by-trial basis, longer estimates for the first stimulus were associated with longer estimates for the second stimulus. The authors concluded that a single pacemaker, single accumulator model with a nonlinear pseudo-logarithmic timescale (see also Taatgen, van Rijn, & Anderson, 2007) best explained their data. That is, in order to perform this task when both intervals were 2 s, participants first of all stored the number (x) of pulses accumulated during the SOA (i.e. between the two start signals), then indicated the end point of the first interval after timing it fairly accurately, and then waited until x pulses had passed again before indicating the end of the second interval. Under this model, only a nonlinear timescale would predict an increase in the estimate of the second interval with increasing SOA. This is because the number of pulses collected during the first SOA contributes to the second estimate and this represents a longer period of real time as the nonlinear scale progresses (i.e. with increasing SOA).

1.1. The present study

In their study, van Rijn and Taatgen (2008) investigated multiple timing in interval production. That is, these experiments examined how participants produce pre-learned intervals in an overlapping context. In contrast, in the present study, we were interested in how people perceive the durations of two overlapping intervals. To this end, we presented participants with two stimuli (S1 and S2) of the same duration (2 s), with variable SOAs. Increasing the SOA had the effect of decreasing the degree of temporal overlap between the two stimuli. Participants reported the perceived duration of each stimulus separately (estimates 1 and 2; E1 and E2).

We applied timing models already described in the literature to the overlapping interval perception context, derived predictions, and compared our results to these. We started with the same three structural constraints that were tested in van Rijn and Taatgen (2008). These structural constraints can be distinguished by the number of pacemakers and accumulators available to the timing system. When only a single pacemaker and single accumulator are available, a calculation is required in order to estimate the intervals. Another timing model described in the literature, the weighted sum of segments model (Matthews, 2013), suggests that there may be an additional constraint in such a single pacemaker single accumulator structure, in the form of a weighting which is applied in the calculation process. The weighted sum of segments model was originally proposed to describe how people judge sequences that are composed of different segments. It posits that in order to estimate an entire sequence length, each segment is timed, a weight is applied to each segment depending on its distance from the end of the sequence (further away receives less weighting), and these weighted segments are summed. Thus, under the structural constraints of a single pacemaker and single accumulator, there are two possible timing models — a simple version and a weighted version.

Two other structures were considered — the single pacemaker, multiple accumulators structure, and the multiple pacemakers, multiple accumulators structure. A calculation is not required for these models, thus a weighted version was not modelled. Theoretically, these two models could have as many accumulators as required, and the multiple pacemakers, multiple accumulators model could have as many pacemakers as required, based on the number of intervals to be timed. However, in this case participants must only time two intervals so we consider models with two accumulators and/or pacemakers. Importantly, when more than one accumulator must operate simultaneously, estimates suffer from dual-task costs. Specifically, according to van Rijn and Taatgen (2008), dual-task costs are assumed to result from the accumulators being slower to update (and therefore missing pulses) when two accumulators operate simultaneously.

Details of how these models were applied to the experimental context of the present study, and the resulting predictions, are described next. Full details of Monte Carlo data simulations are provided in Appendix A.

1.2. Predictions

In applying the models to the experimental context we tested, three assumptions were made. First, because participants reported each perceived interval separately (i.e. not in an overlapping fashion, as in the study by van Rijn & Taatgen), the pacemaker was assumed to be reset for reporting the perception of the second interval. Second, for models in which there is only one accumulator, it was assumed that the three segments of the overlapping intervals would be timed separately, and then combined (in different ways depending on the model) to produce estimates 1 and 2 (E1 and E2). The three segments are: (1) from the start of S1 until the start of S2 (i.e. the SOA), (2) from the start of S2 until the end of S1 (i.e. the overlap, or interval 1 − SOA), and (3) from the end of S1 until the end of S2 (i.e. in this case, this is again the SOA as each interval was 2 s). Third, for models in which there were dual-task costs these were assumed to affect estimates of both intervals (E1 and E2) equally. Table 1 summarizes the four models and their predictions, and Fig. 1 illustrates how the models would function when a nonlinear timescale is assumed. A nonlinear timescale is used for the illustration because in most of the models, a nonlinear timescale predicts the greatest effects of SOA on estimates. However, as previously mentioned, the important issue of whether time is represented linearly or nonlinearly in the mind is not yet settled.

If the timing system is constrained structurally by having only one pacemaker and one accumulator (SPSA, referred to as the single accumulator model in van Rijn & Taatgen, 2008), in order to complete the task in the present experiments, the most likely strategy is that the three segments are timed, the number of pulses is stored, and then calculations are performed to produce E1 and E2. E1 would be calculated as the sum of segment 1 and segment 2; E2 would be calculated as the sum of segment 2 and segment 3 (this is the simple application of the SPSA structure, named $SPSA_{simple}$; see Fig. 1A). If time is represented by a linear timescale, these calculations would be similarly accurate across SOAs. However, if time is represented nonlinearly, E1 would remain unchanged by SOA, while E2 would decrease with increasing SOA. This is because the pulses become more spaced out as the entire sequence lengthens, primarily affecting segment 3. This would result in fewer pulses being collected during segment 3 than segment 1 of the same objective length, as SOA increases. This model posits that timed intervals are not subject to dual-task costs because there is only one accumulator. Thus, there is no competition between two accumulators operating simultaneously.

In the weighted application of the SPSA structure ($SPSA_{weighted}$), based on the weighted sum of segments model (Matthews, 2013), a calculation is also performed in order to produce estimates. However, the $SPSA_{weighted}$ model assumes that the pacemaker is reset for each segment[1], that time is represented nonlinearly, and that in calculating

[1] While Matthews (2013) noted the similarities between the structural constraints of his model and a single pacemaker single accumulator timing model, he did not explicitly define the number of pacemakers and accumulators involved. Instead, the weighted sum of segments model assumes that each segment is represented by "a separate negatively-accelerated function of its duration". However, whether this would be generated by one pacemaker which restarts, or separate pacemakers for each segment, is largely academic.