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ScienceDirect

Procedia - Social and Behavioral Sciences 126 (2014) 141 – 150

Procedia
Social and Behavioral Sciences

ICTTP 2014

Unifying prospective and retrospective interval-time estimation: A fading-Gaussian activation-based model of interval-timing

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Abstract

Hass and Hermann (2012) have shown that only variance-based processes will lead to the scalar growth of error that is characteristic of human time judgments. Secondly, a major meta-review of over one hundred studies (Block et al., 2010) reveals a striking interaction between the way in which temporal judgments are queried and cognitive load on participants' judgments of interval duration. For retrospective time judgments, estimates under high cognitive load are longer than under low cognitive load. For prospective judgments, the reverse pattern holds, with increased cognitive load leading to shorter estimates. We describe GAMIT, a Gaussian spreading-activation model, in which the sampling rate of an activation trace is differentially affected by cognitive load. The model unifies prospective and retrospective time estimation, normally considered separately, by relating them to the same underlying process. The scalar property of time estimation arises naturally from the model dynamics and the model shows the appropriate interaction between mode of query and cognitive load.

Selection and peer-review under responsibility of the Organizing Committee of the International Conference on Timing and Time Perception.

Keywords: Interval-timing; Activation-based model; Time perception; Retrospective and prospective timing

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1. Introduction

Extensive empirical evidence (Gibbon, 1977; Gibbon & Allan, 1984; Matell & Meck, 2000; Meck, 2005) suggests that time-estimation errors in interval times grow approximately linearly with the size of the estimate. Known as the *scalar property* of time estimation, this sets a hard constraint on the nature of the underlying processes involved in time estimation (Hass & Herrmann, 2012) and remains the *sine qua non* of time-estimation models.

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Selection and peer-review under responsibility of the Organizing Committee of the International Conference on Timing and Time Perception.
doi:10.1016/j.sbspro.2014.02.348

Secondly, in a careful meta-analysis of well over one hundred studies, Block et al. (2010) established that human adults' perception of the passage of time differs according to whether they are forewarned that they will need to make a timing judgment, and are therefore actively attending to its passage (*prospective* time estimation), or whether they are required to make an unexpected, after-the-fact judgment of the passage of time (*retrospective* time estimation). And finally, this difference is heavily modulated by cognitive load, showing a classic cross-over interaction in which either prospective or retrospective judgments are longer depending on whether the participant experiences high or low cognitive load (Figure 1).

We will show that a model of time perception based on the idea of sampling a fading-Gaussian activation trace, GAMIT, naturally captures all three of these critical properties of interval time estimations by considering not only the amount of activation decay of the Gaussian, but also the rate at which decay is occurring.

1.1 An overview of existing models of interval timing

There are three major paradigms for interval-time judgments: (1) pacemaker-accumulator models, (2) multiple oscillator-coincidence detector models (also sometimes called timestamp models), and (3) memory or neural process models. The first class of models relies on an internal pacemaker that emits regular, short pulses that are counted by an accumulator. The number of pulses stored in the accumulator gives the measure of the time that has passed (Church, 1984; Gibbon et al., 1984; Wearden, 1991, 2001; Taatgen et al., 2007). A second class of models relies on multiple neuronal oscillators with coincidence detectors associating particular patterns of firing with given time intervals, effectively time-stamping when an event occurs (Church & Broadbent, 1990; Matell & Meck, 2000; Miall, 1989). An alternative type of oscillator-based timing model (e.g., Brown et al., 2000) assumes that some representation of the state of an already-running set of oscillators (started, say, at the birth of the individual), is associated with each event in memory, in essence, as one of the features of the event. The third class of models involves recovering the passage of time from a neural process that is decaying (Lewis & Miall, 2006; Staddon & Higa, 1999) or increasing (Reutimann et al., 2004). Here, the current state or change in state of the activation trace allows the system to recover the passage of time.

1.2 Interval timing and the scalar property

Interval timing operates in the range from half a second to several minutes. Here humans and other animals show very similar abilities. The *scalar property* or time-scale invariance (Gibbon, 1977) states that the width of this distribution is directly proportional to the length of the interval. So, for example, the standard deviation for a distribution of estimates of an interval of 2X seconds will be (approximately) twice that for an interval of X seconds. This effect is very widely replicated with humans, rats and pigeons (see Gibbon & Allan, 1984; Gibbon et al., 1997; Matell & Meck, 2000; Meck, 2005). Although some studies report a greater than linear increase of the timing errors (reviewed in Hass et al., 2008; Gibbon et al., 1997; Grondin, 2001).

No model that we are aware of accounts for the scalar property as an unavoidable consequence of the way the timing mechanism works (Hass & Hermann, 2012; Hass et al., 2008). For example, models based on repetitive clock-like processes have *less* intrinsic variability than predicted by the scalar property and must introduce assumptions as to why the cognitive system cannot use these more precise quantities. Hass and Hermann use information theoretic arguments to show how the scalar property places several important restrictions on the nature of any interval timing mechanism. In particular, they show that, in order to display scalar error profiles, the neural process underlying time perception must be based on a measure of growing variance in the system. Power law decay functions found in memory-decay models would give rise to more than linear growth in error while the errors in accumulators and oscillators grow too slowly. Accumulator models base their estimates on mean number of accumulated ticks or oscillations. However, according to the *Central Limit Theorem,* such estimates have errors that grow with the square root of the total. Only with logarithmic decay does a constant error around activation values convert to a scalar error in magnitude.

Accumulator models cannot account for the scalar property of time without positing a secondary process that modifies the shape of the error distribution (Hass & Herrmann, 2012). Gibbon (1977) acknowledges this problem for the original Scalar Expectancy Theory (SET) pacemaker-accumulator model. In SET, the pacemaker is a Poisson process and variance in a cumulative Poisson process grows according to the square root. Gibbon et al. (1997) get around this by attributing the error primarily to a multiplicative factor associated with the comparison of accumulated estimates and their counterparts in memory, relying on a mathematical argument by Gibbon (1992). Decisions as to whether the clock has reached a given value are performed by seeing if the ratio of the accumulated value and the valued stored in memory is within a certain threshold. This ratio induces the scalar property and is