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Special Issue: Time in the Brain

Forum

Towards Ecologically Valid Interval Timing

Hedderik van Rijn ^{1,*}

Research on interval timing has provided significant insight into how intervals are perceived and produced in well-controlled laboratory settings. However, for timing theories to explain real-world performance, it is imperative that they provide better quantitative predictions and be applicable to timing tasks that are relevant in ecologically valid settings.

Introduction

Whether it is using a well-timed silence during a speech to increase rhetorical effectiveness, determining whether one can finish reading a paragraph in the newspaper while keeping an eye on the children, or deciding when to initiate the final, irreversible stage of a landing procedure of a large commercial airplane, timing is an essential feature of almost

all complex, ecologically valid behavior. Consequences of inaccurate timing range from less-effective communication and unintended but innocuous artwork on the walls, to lethal accidents. Thus, being able to predict how and when humans accurately estimate the duration of relative intervals from hundreds of milliseconds to a few minutes is crucial to explain how optimal behavior in complex tasks can be achieved.

Regrettably, although decades of research on interval timing have provided significant insight into how intervals are perceived and produced in well-controlled laboratory settings (e.g., [1]), the fact that these settings bear little relation to ‘real life’ makes it difficult to generalize the obtained knowledge to realistic task settings [2]. For example, although laboratory studies have demonstrated that timing is influenced by a wide spectrum of external factors, it is unclear to what extent these effects generalize to temporal aspects during decision making (e.g., [3]) or, more specifically, to a pilot’s time-based decision about initiating the final stage of a flight. For the timing field to have an impact in the real world, it is imperative that timing theories should: (i) provide quantitative predictions; and (ii) be applicable to the type of timing tasks relevant in ecologically valid settings. Below I argue why current theories fail on either or both accounts, and what aspects need to be taken into account in future theorizing.

Characteristics of Ecologically Valid Timing

A critical challenge for models based on laboratory-based timing tasks is that these types of models all describe the timing of an interval that is purposively started in the present and will have a well-defined end sometime in the near future, allowing participants to actively attend to the passage of time (Box 1). This type of prospective timing is typically explained by assuming that there is a well-defined ‘start signal’ indicating the onset

of the interval, after which the accrual of neural information or changes in the state of a network tracks the passing of time. However, when a salient event is observed in the real world, it is possible that at a later point in time one will need to assess how long ago that event happened. As events are encountered frequently, theories should be able to explain how we can keep track of time for a number of these events without requiring a single clock to be explicitly reset at the start of each interval.

Although some models explicitly account for this possibility (for a review see [4]), this is difficult to achieve for the majority of timing models given their intrinsic properties. That is, prospective timing theories typically assume that time is estimated in one continuous take during which attention is focused on the passing of time. These models either (often implicitly) predict that estimation of multiple concurrent intervals is impossible or hinge on complex cognitive strategies using ‘temporal arithmetic’ [5,6]. The emphasis on the estimation of singular intervals is unsurprising, as there seems to be a clear dissociation between the difficulty people have with estimating multiple intervals in explicit timing tasks in laboratory settings and the ease with which humans seem to estimate the temporal characteristics of concurrent intervals in real life. However, a recent animal study [7] supports the view that concurrent timing is feasible, as rhesus monkeys can simultaneously monitor and respond to multiple temporal intervals without revealing signatures of temporal arithmetic. Thus, future models of interval timing should be able to explain how we, during a conversation with a passenger while driving, can keep track of the durations of the passenger’s speech pauses, of how long ago the overtaking car disappeared in the mirror’s blind spot, and whether to again check the navigational device for the next instruction.

Box 1. Retrospective, Prospective, and Continuative Timing

The traditional distinction in the timing literature has been between retrospective and prospective timing. Retrospective timing is estimating, in hindsight, how much time has passed since an event in the past. Prospective timing, by contrast, is actively estimating how much time is passing between a marked onset and offset. The majority of studies focus on prospective timing, if only because this paradigm is easier to incorporate in repeated-measure experiments, and the theoretical explanations of the two accounts are often incompatible (but see e.g., [4]). However, in real life many examples of timing do not fit this binary distinction, as one often notices the duration of an ongoing interval. For example, the typical realization that a process is already taking a long time but that one will wait a bit longer for a process to finish is a clear combination of retrospective and prospective time estimation. As this is a clear example of the continuation of time, we have earlier described this as Continuative Timing [12] (Figure 1), and have argued that theories of ecologically valid timing should provide a theoretical account for this type of timing that is neither fully retrospective nor prospective.

Figure 1. Temporal Relationships between Retrospective, Continuative, and Prospective Timing.

Lacking Quantitative Predictions

One of the causes of limited external validity in science in general is that individual empirical results can often not easily be integrated into an overarching domain theory. Interestingly, this is not the case for the interval timing domain, as the large majority of the empirical results is explained in terms of the pacemaker/accumulator framework. According to this framework, a pacemaker emits pulses that are accumulated to reflect the amount of time that has passed since the last reset. By entering the accumulated value in a memory store, new durations can be compared with earlier experienced durations, and behavioral performance can be adapted to temporal regularities.

However, the ease with which empirical results can be explained in terms of this framework is also its bane, as the numerous degrees of freedom associated with this theory make it overly flexible [8]. An example of this flexibility is that slowing of subjective time can be explained by a multitude of parameters (e.g., slowing of the pacemaker, slower or noisier readout of the pacemaker, affected temporal memories). Because of this flexibility, this framework can account for almost all possible empirical results, rendering it impossible to quantitatively predict temporal performance in complex task settings.

A number of new models have been proposed in recent years that aim for

neurobiological realism or more stringent mathematical descriptions of decision processes (e.g., [9]). Although these computational (neuroscience) models are essential tools for testing the biological or computational viability of theories and provide inherent, biological modeling constraints, these models are typically far removed from the computational modeling of complex, ecologically valid tasks. For example, the original Striatal Beat Frequency model provides an elegant neurobiological account of how the brain could keep track of time. However, how stimuli that have to be timed are perceived, how memory traces of the intervals are amassed, or how the firing of time neurons results in the execution of, for example, a key press, is not specified.

Box 2. Bringing Ecologically Valid Timing into the Laboratory

Information-processing models of interval timing, proposed in the 1950s to replace associational accounts of learning and conditioning, are still at the basis of the current pacemaker/accumulator theories. Later extensions have made these models more generally applicable to, for example, attentional modulations. Ultimately, however, these models do not sufficiently consider external influences on interval timing in ecological settings, as they are mostly suited for capturing simple laboratory experiments. However, it is almost never necessary to estimate an interval for the sake of estimating an interval; timing always subserves another action and is often completely implicit. To study ecologically valid timing, research should focus on tasks in which timing is (mostly) implicit by using complex simulations of real-life scenarios or tasks with implicit temporal regularities. For example, we have described an experiment in which paying attention to temporal regularities would improve performance but was not strictly necessary [13]. Participants were oblivious to the role of time, yet their behavior showed sensitivity to time. Only when these types of tasks, in addition to the traditional paradigms, become a standard paradigm in the empirical toolbox of temporal cognition researchers can we achieve a better understanding of the influence of time on everyday behavior.

Obviously, accounting for all of these auxiliary mechanisms is not something that can be expected of a theory that aims at providing a detailed, neurobiological account of a specific phenomenon. To allow the testing of interval timing models in more realistic task settings, a more extensive model of cognitive functioning is required.

A proven approach is to incorporate models of specific tasks into a cognitive architecture [10] that provides validated accounts for auxiliary processes such as memory storage or motor responses. The integration of timing in a more general processing framework [11] would allow researchers to account for a broad range of more ecologically valid timing tasks or even human–robot interactions (Box 2). Although the adoption of a simple, static pacemaker/accumulator model may have been practical for early integrative models, modern work should utilize the modular nature of cognitive architectures

and replace these too-simplistic models with more plausible and better-constrained accounts of interval timing [8], yielding more precise, quantitative predictions of temporal performance.

To conclude, the interval timing domain currently lacks an integrative, well-constrained framework that can be used to provide quantitative predictions of temporal behavior in ecologically valid, real-world tasks.

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