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## Chapter 9: Models of psychological time revisited\*

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### Introduction

Theorists have taken two seemingly different approaches to explaining, or modeling, psychological time (Block, 1990). These approaches have appeared under several guises. Ornstein (1969) referred to them as the sensory-process approach and the cognitive approach. Sensory-process models „postulate some sort of ‘time-base’, a repetitive, cumulative, pulse-dispensing mechanism which delivers internal time signals, an ‘organ’ of time” (p. 25). Ornstein claimed that this type of model has not provided a useful way to understand duration experience. This approach may also have difficulties explaining why cognitive, or information-processing, variables influence duration experience. The other class of model includes various proposals concerning the important cognitive factor underlying duration experience, such as „images” (Guyau, 1890; 1988), „changes,” (Fraisse, 1957; 1963), „mental content” (Frankenhaeuser, 1959), „storage size” (Ornstein, 1969), and „contextual changes” (Block & Reed, 1978). According to some proponents of sensory-process models, cognitive models cannot easily explain the near-linear psychophysical relationship between physical and psychological duration, as well as the possible influence of physiological variables such as body temperature.

### Timing with or without a timer

The important difference between the two approaches is not that the first concerns sensory processes and that the second concerns cognitive processes. Instead, the first class of model proposes timing with a timer, whereas the second proposes timing without a timer (Ivry & Hazeltine, 1992). In timing-with-a-timer models, a pacemaker mechanism underlies

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the psychological timing system. Two major variants are chronobiological and internal-clock models (Block, 1990).<sup>1</sup> In timing-without-a-timer models, subjects construct psychological time from processed and stored information - that is, some salient aspect or byproduct of information processing. Variants of this kind of model include attentional, memory storage, and memory change models (Block, 1990).

Piéron (1923) was one of the first researchers to discuss the possible relationship between body temperature and duration experience. Subsequently, François (1927) and Hoagland (1933) obtained such evidence, which supports a possible timing-with-a-timer model. Hoagland (1933; see also 1966) proposed that a *master chemical clock*, or temporal pacemaker, in the brain regulates time-related behaviors and judgments. The evidence suggested that the rate of repeated time productions - involving counting at the rate of one per second - increases as a function of body temperature. More recent evidence suggests that duration judgments of many minutes (e.g., hourly productions) are correlated with body temperature (Campbell & Birnbaum, 1994). Although the relationship between body temperature and shorter duration judgments is often inconsistent (Hancock, 1993), changes in body temperature do seem to lead to systematic changes in the rate of psychological time (Wearden & Penton-Voak, 1995). One possibility is that body temperature influences general arousal level, which thereby influences the rate of a pacemaker mechanism (Wearden & Penton-Voak, 1995). The problem with postulating that a pacemaker or master biochemical clock directly influences time-related behaviors and judgments is that temperature may also influence brain processes that subserve attentional, memory, and other cognitive processes. Variations in these processes probably have little or no effect on body temperature. Because cognitive variables (e.g., attentional demands of a task) influence duration experience, cognitive processes may directly mediate temporal behaviors and judgments. Body temperature may indirectly influence temporal behaviors and judgments by altering whatever cognitive processes subserve psychological time (Block, 1990).

Theorists have proposed a large number of cognitive models of psychological time. They have stated these mostly in the form of a „variable-*x* hypothesis,” where one may substitute any of several variables for *variable-x* (e.g., input segmentation, complexity-of-coding, attentional selectivity). Each of these variables is typically the only one that the researcher manipulated. A few models have attempted to be

more general. Consider, for example, Doob's (1971) model (Figure 1, p. 174). This model illustrates a taxonomy of time that depicts interactions involving the „intricate, multivariate phenomenon of time” (p. 30). The details are relatively unimportant. For present purposes, we note that although this model may seem comprehensive, it is not a functional (e.g., information-processing) model of temporal behavior or judgment.

Block (1985) proposed a contextualistic model in which temporal experience is a product of four kinds of interacting factors (Figure 2, p. 175). Again, the details are relatively unimportant, because this model is only a little more functionalistic than Doob's. The main advantage of models such as Doob's (1971) and Block's (1985) is heuristic: these models remind us that psychological time involves complex interactions of various organismic and environmental variables. The main disadvantage of these models, as noted above, is that they do not „relate in a functional way to the empirical findings [they are] supposed to represent” (Michon, 1985, p. 26). Although both models depict interactions of variables, several functional issues remain: (a) Which interactions are important in particular situations and which are not? (b) What is the nature of the higher-order interactions? (c) How are the underlying processes sequenced, as in a functionalistically oriented information-processing model of temporal behavior?

Cognitive psychologists and others have occasionally proposed models resembling internal-clock models, but these usually involve timing without a timer. For example, Lashley (1951) thought that practiced movement sequences are structured as individual elements organized into chunks which are executed as part of a motor program for the action sequence. Because he proposed that a motor program is executed without the need for feedback, it needs an internal-control process to time elements. Researchers have searched for such a common mechanism that is able to stabilize motor programs despite changes in states of the organism, changes in contextual stimuli, changes in equipment or instruments used for the performance, and so on. The important question of how movement sequences are timed is still largely unresolved, as is the question of whether we need to propose an internal-clock mechanism. Motor programs may contain internal, hierarchically organized information about timing relationships, so a pacemaker mechanism may be unnecessary. Alternatively, even such information about timing relationships may rely on a pacemaker for some basic calibration (see Senjen, this volume, chapter 2).

<sup>1</sup> An example of an internal-clock model is also described in chapter 4 by H. Fisler.

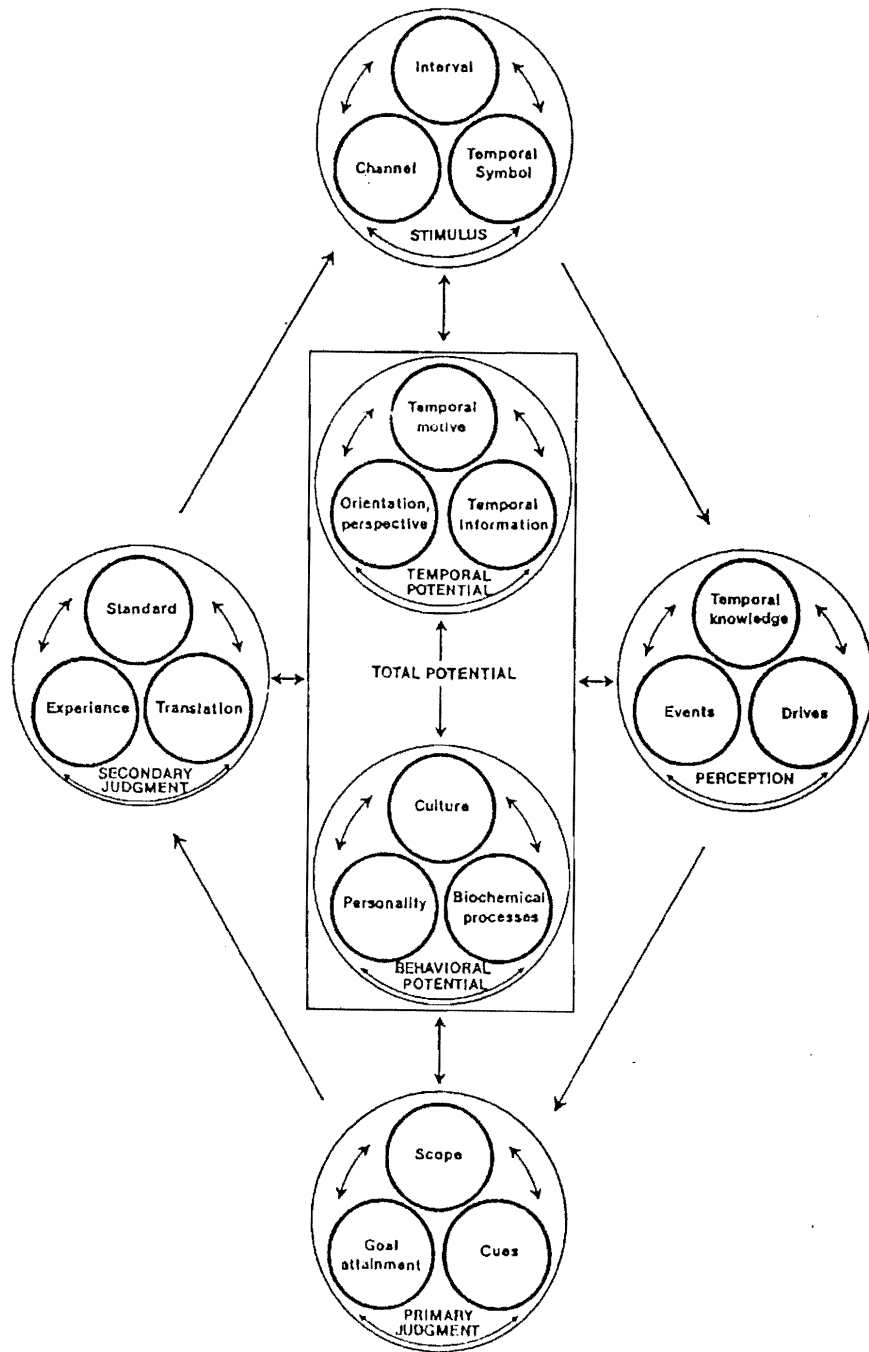


Figure 1: Doob's (1971) taxonomy of time.

In the remainder of the chapter, we review various formal models of psychological time. We propose the attentional-gate model, which reconciles the two approaches. This model is somewhat isomorphic with contextual-change models of experienced and remembered duration.

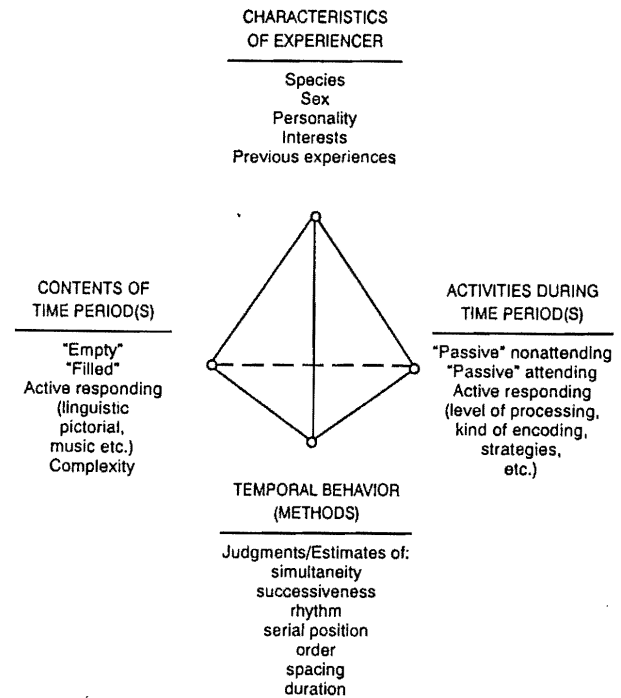


Figure 2: Block's (1985) contextualistic model of duration experience.

### Treisman's Model

Treisman (1963) proposed an influential model of an internal clock underlying human temporal judgment (Figure 3, p. 176). He postulated a *pacemaker* that produces a regular series of pulses, the rate of which varies as a function of input from an organism's *specific arousal center*. In his view, specific arousal is influenced by external events, in contrast to general arousal, which depends on internal mechanisms such as those underlying circadian rhythms. A *counter* records the number of pulses in a *pathway*, and the total is transferred into a store and into a *comparator* mechanism. A *verbal selective mechanism* assists in retrieving useful information from the store. This is presumably a long-term memory store

containing knowledge of correspondences between total pulses and verbal labels, such as 20 s, 1 m, and so on.

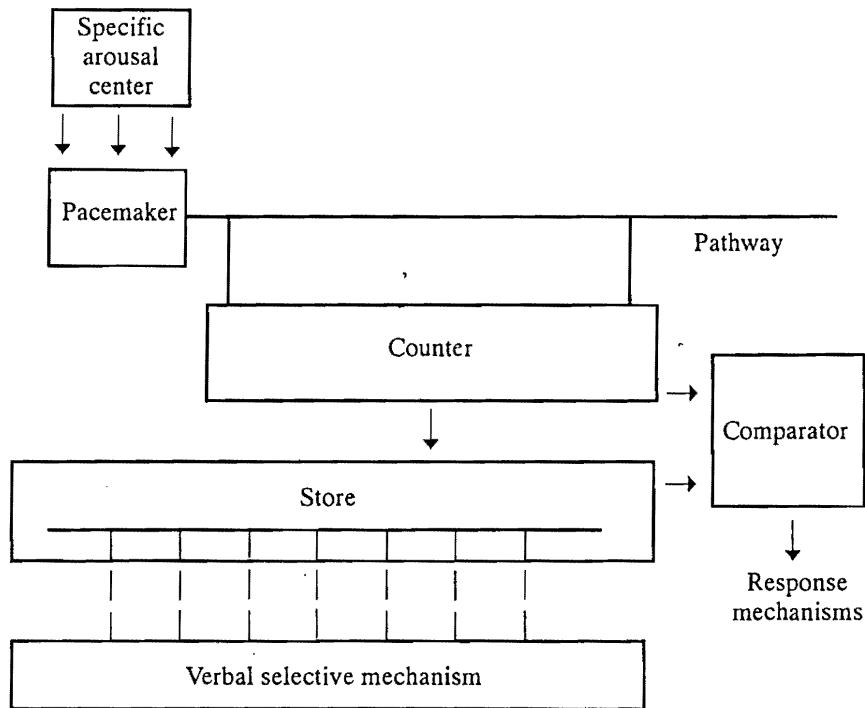


Figure 3: Treisman's (1963) model of the internal clock.

Subsequently, several theorists proposed that the alpha rhythm may reflect the frequency of the pacemaker component of the hypothetical internal clock. Treisman (1984) attempted to determine whether this is the case. However, his data do not support the view that arousal, at least as it is reflected in alpha frequency, influences the pacemaker rate. In a recent modification of this internal-clock model, Treisman and his colleagues (Treisman et al., 1990; Treisman, 1993) proposed a more complex pacemaker, which includes a *calibration unit* that can modulate the

pulse rate. In our view, this minor modification does not rectify the limitations inherent in the model.

## Scalar-timing model

Contemporary behavioral psychologists, who draw and test inferences about timing processes in animals, have proposed internal-clock models that resemble Treisman's (1963; 1993) model. These researchers typically investigate time-related behavior of animals such as pigeons and rats during relatively short time periods (seconds to minutes). The general finding is that animals are sensitive to different stimulus durations and time-based schedules of reinforcement.

Figure 4 (p. 177) shows the canonical model embodying the theory underlying these explanations, called *scalar timing theory* or *scalar expectancy theory*. Because this model provides an excellent account of a wide variety of evidence, many researchers have adopted it (e.g., Allan, 1992; Church, 1984; Gibbon & Church, 1984; Gibbon et al., 1984; Roberts, 1983). The present account is rather brief. We recommend Church's (1989) excellent chapter for additional details, and also Lejeune & Richelle's chapter (this volume, chapter 8), which contains an especially valuable discussion of cross-species comparisons.

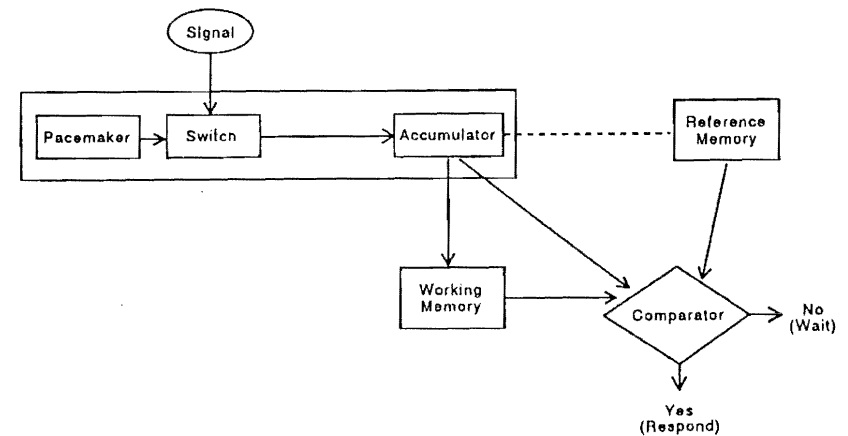


Figure 4: Scalar timing model (Church, 1984; Gibbon, 1984).

This model accounts for time (duration) perception and time production by proposing an internal clock, memory stores, and a decision mechanism. The internal-clock consists of a pacemaker, a switch, and an accumulator. The *pacemaker*, operating like a metronome, automatically

and autonomously generates more or less regularly spaced pulses (at a rate of  $\lambda$  pulses per second). When the organism perceives an external timing *signal* indicating the beginning of a time period, the *switch* operates (perhaps with a slight lag, influenced by attention), thereby allowing pulses to pass through to an accumulator. The *accumulator* integrates and holds the total pulse count during the time period ( $\Delta t$ ). Perceived duration is a monotonic function of the total number of pulses transferred into the accumulator. On any trial, the contents of the accumulator are transferred into a *working memory* store for comparison with the contents of the *reference memory* store. The *reference memory* store contains a long-term memory representation of the approximate number of pulses that accumulated on past trials. This number is then transferred to the comparator with some bias,  $K^*$ , a memory storage constant that may be slightly less than or greater than 1. The *comparator* compares the contents (total pulse count) of the two stores.

## Animal evidence

The peak procedure, which uses a modified discrete-trials fixed-interval (FI) schedule, is a common method used to explore animal timing. A relatively long, variable interval separates each trial. The onset of a discriminative stimulus such as a light signals the start of each trial. On most trials, the first response occurring after a FI (e.g., 30 s) has elapsed since the start of the trial is reinforced; then the discriminative stimulus is turned off. On other trials, which are the most important ones for testing the theory, the animal receives no reinforcement, and the discriminative stimulus is turned off only after a relatively long interval, usually at least twice the FI (e.g., 60 s). Averaged across many such trials, the typical response rate is approximately a Gaussian (bell-shaped) function of time since the start of the interval. This timing behavior reveals a scalar property: regardless of FI length, the average response rate at any time, expressed as a proportion of the peak rate, is a function of the proportion of the total duration that has elapsed. In other words, the normalized response-rate curve does not vary much from one FI length to another. The internal clock model handles this general finding by proposing that the response rate increases in probability as the comparison of working memory and reference memory reveals a similar total pulse count.

In the peak procedure and other similar procedures, the switch operates at the onset of the discriminative stimulus, with some slight lag attributable to attentional processes, and the accumulation of pulses begins. If an animal learns that the temporary offset of the timing signal will delay reinforcement by the length of the offset duration, it shows ap-

propriate responding - that is, a temporally displaced response rate function (Roberts & Church, 1978). This implies that the internal clock functions like a stopwatch, cumulatively timing the duration. The start/stop button may be switched off for the duration of the offset of the timing signal. (This represents a slight elaboration on Treisman's model, which did not propose a counter-stopping mechanism.)

## Human evidence

Because the scalar-timing model can time various periods, including interrupted fixed-interval schedules, it is able to handle virtually all extant animal-timing data. However, the model does not take into account factors that are more prominent in humans than in other animals. In particular, it is not easily able to explain why cognitive factors (e.g., attention, strategies, information-processing tasks) influence temporal behaviors. This seems largely a consequence of methodological limitations or neglect: few animal timing researchers have explored or discussed the effects of attentional manipulations, which have been a focus of considerable research on human prospective duration timing. In addition, organisms may use repetitive or chained behaviors as „external clocks” to time intervals; that is, they may engage in movements for an appropriate amount of time while they wait for reinforcement to be enabled (Pouthas, 1985). Thus, activities (such as strategies) of an organism during a time period influence its time-related behaviors. The scalar-timing model does not incorporate this kind of „external” timing process.

In short, internal-clock models proposed by behavioral psychologists investigating timing in nonhuman animals seem somewhat limited (Block, 1990). Until these models consider the role of cognitive factors, such as attentional allocation, they will not be able to generalize to explaining human duration judgment. The work of Richelle and Lejeune (see Lejeune & Richelle, this volume, chapter 8; Richelle & Lejeune, 1980; Richelle et al., 1985) is a notable exception. They have conducted comparative research involving several species, including humans, and have included a role for cognitive factors. Richelle et al. (1985) thought that the answer to the problem is to propose „as many clocks as there are behaviors exhibiting timing properties” (p. 90). We take a different view. We propose a model containing a single „cognitive clock,” a model with seemingly broad explanatory power (see „attentional-gate model,” later in this chapter).

To justify such a model, we first consider the more cognitively oriented human research. We show that without additional elaboration the

scalar-timing model cannot handle evidence on human timing and temporal judgment.

### Thomas's attentional model

Several theorists have proposed models of psychological time in which attention to time, or temporal information processing, plays a major role. Thomas and his colleagues (Thomas & Cantor, 1975; Thomas & Weaver, 1975) developed and tested a mathematical model in which attentional allocation influences duration judgments. This model (Figure 5, p. 181) is the most explicitly formulated attentional model of psychological time. It is expressed as the functional equation:  $\tau(I) = \alpha f(t, I) + (1 - \alpha) g^*(I)$ . The model says that the perceived duration  $\tau$  of an interval containing certain information  $I$  is a monotonic function of the weighted average of the amount of information encoded by two processors, a temporal information processor  $f(t, I)$ , and a nontemporal information processor  $g^*(I)$ . The organism divides attention between the two processors, which function in parallel. Perceived duration is weighted (with probability parameter  $\alpha$ ) to optimize the reliability of the information that each processor encodes, because as more attention is allocated to one processor, the other becomes more unreliable. As  $\alpha$  approaches 1, the subject encodes more temporal information, and as  $\alpha$  approaches 0, the subject encodes more nontemporal information. If less stimulus information occurs during the to-be-judged duration, the organism allocates more attention to temporal information, and  $f(t, I)$  is more heavily weighted. If a task demands more information processing, the organism allocates more attention to this nontemporal information, and  $g^*(I)$  is more heavily weighted.

Although Thomas and his colleagues studied only human duration judgments of stimuli presented for less than 100 ms, one may consider the model to be a general model of temporal information processing, even involving longer time periods (Michon, 1985).

The strengths of this model complement the strengths of the scalar-timing model. Extant formulations and empirical tests of the scalar-timing model only use the concept of attention in a very limited way (see, for example, Allan, 1992; Meck, 1984). Because attention plays a critical role in Thomas's model, it handles an aspect of the human data that scalar-timing models do not. It also makes slightly more precise terminology such as *attention to time* and *temporal information processing*, which Block (1990) criticized as being overly vague. The model adds precision to these terms by implying that attending to time is like attending to stimulus information in that both processes require access to the

same limited resources. However, Thomas's model is deficient in handling the animal-timing data, as well as the role of physiological (non-cognitive) factors. Because it assumes a constant pool of attentional resources, it does not consider arousal level or variations in alertness attributable to circadian rhythms and other biological factors. It is also too passive: Thomas proposed that stimulus information alone determines the allocation of attention and that strategies are not involved. The model needs a concept of attention along the lines of Kahneman's (1973) resource model. Kahneman argued that arousal determines the total attentional resources available at any moment to meet information-processing demands. Thus, temporal information processing is influenced not only by characteristics of the information-processing task, but also by momentary arousal level and, hence, total available resources. We need this modification of Thomas's model to handle new findings such as the fact that increased alertness, such as when a person is under the influence of stimulants like methamphetamine, lengthens duration experience (Frankenhaeuser, 1959; Hicks, 1992).

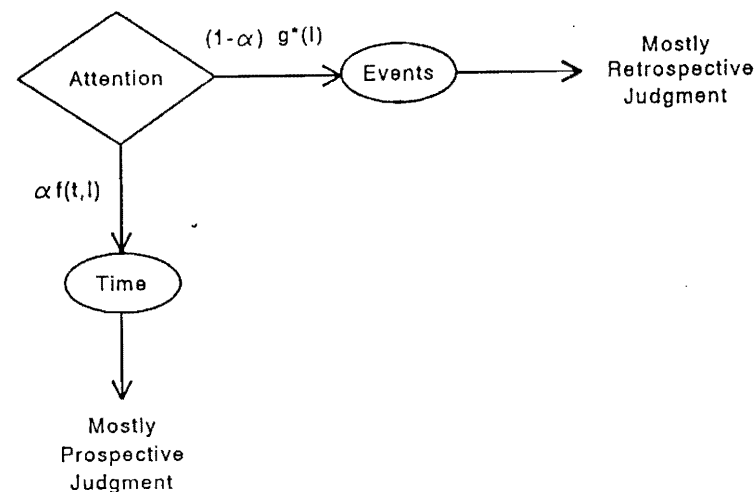
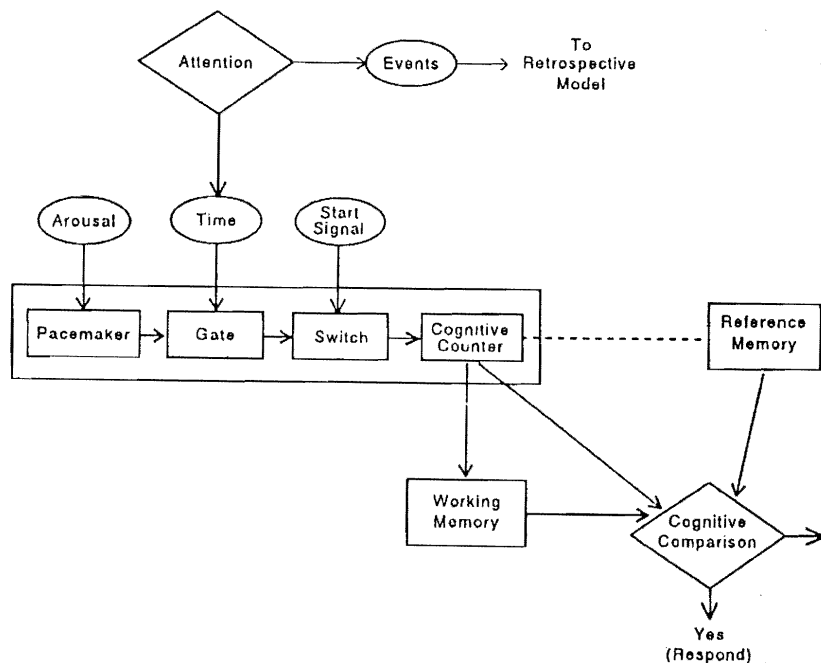


Figure 5: Thomas's (Thomas & Cantor, 1975, Thomas & Weaver, 1975) functional equation diagrammed as a model.

## Attentional-gate model

We propose a model combining features of Treisman's (1963) model, the scalar-timing model (Church, 1984; Gibbon & Church, 1984; Gibbon et al., 1984), and Thomas's (Thomas & Cantor, 1975, Thomas & Weaver, 1975) model. We call this the *attentional-gate model* (Figure 6, p. 182). Consider first a version of the model that can handle the kind of prospective duration timing which both Treisman's and scalar-timing models are designed to handle. The critical feature of prospective timing is that the organism's behavior is focused on temporal information, as a result of either learning or instructions.



**Figure 6:** The attentional-gate model of prospective duration timing.

We propose that a *pacemaker* produces pulses at a rate which is influenced by both general (e.g., circadian) and specific (e.g., stimulus-induced) *arousal*. Each occasion on which an organism attends to time, as opposed to external stimulus events, opens a *gate*. This allows the pulse stream to be transmitted to subsequent components. At the onset of a duration, indicated by some *start signal*, the switch allows the pulse stream to be transmitted to the *cognitive counter*, where pulses are counted, or summed over time. (We call this component a *cognitive*

*counter*, rather than simply an *accumulator*, because controlled cognitive processes, such as attention, influence the input to it.) The rest of the model contains functional components analogous to those in the scalar-timing model. The momentary total pulse count in the cognitive counter is transferred to a *working memory* store. (This process may occur only when attention is deployed, in contrast to the analogous process in the scalar-timing model, which is assumed to be automatic and continuous.) In addition, a *reference memory* store contains a record of the average total number of pulses that accumulated in the past before a certain time period was complete. (In humans, the reference memory store may also contain learned correspondences between pulse totals and verbal labels for temporal units.) If the momentary total pulse count in working memory approximates the total in reference memory, a *cognitive comparison* (probably also involving attention) results in the organism signaling the end of the time period or making some other duration-dependent response. If fewer than the required number of total pulses have been counted, the organism waits or makes a shorter duration judgment.

At present, little or no evidence (whether from animals or from humans) definitively tests some details of this model. For this reason, we are unsure about the relative location of two components, the attentional gate and the switch (Zakay & Block, 1994). It may be more appropriate to locate the switch before, instead of after, the attentional gate. Neither logical analysis nor empirical evidence seems to favor one order over the other. Differences in the dynamics of these two components suggests that they are separate components, instead of simply being a single *attentional switch* (cf. Allan, 1992; Meck, 1984): The switch operates as a result of the organism's processing of external signals, whereas the gate operates as a result of the organism's internal allocation of attentional resources. We are also unsure about the appropriate metaphor to use for the functioning of the gate. Attention to time may be viewed as opening the *gate* wider or more frequently, thereby allowing more pulses to pass through it to the cognitive counter. Neither logic nor evidence is available to distinguish these metaphors.

The attentional-gate model contains two important modifications to extant internal-clock models. First, it incorporates the notion that a subject may divide attentional resources between attending to external events and attending to time (Thomas & Cantor, 1975; Thomas & Weaver, 1975), and it specifies the consequences of each. Attending to time is necessary for pulses to be transmitted to the cognitive counter. While the duration is in progress (i.e., while the switch is allowing pulses to pass to the cognitive counter), the number of transmitted pulses

is a function of two factors: (a) the pulse rate, which is influenced by general and specific arousal, and (b) the proportion of time the gate is open, or the width it is open, which is influenced by the amount of attention allocated to time.

Few animal-timing experiments have presented varied stimulus information during a time period, such during a FI or DRL (differential reinforcement for low rate of responding) schedule (see, however, Macar, 1980). A start signal occurs at the beginning of a time period, but that is the only external information presented. An easy way to test the attentional-gate model would be occasionally to present varied stimulus information (novel events that have not been learned as relating to the reinforcement schedule) during the time period. Using the peak procedure, we predict a peak-shift right. That is, we expect the peak rate of responding to be temporally displaced, occurring later than when no such information is presented. A colleague has suggested that the opposite - a peak shift left - may instead occur. The reason is that the animal may realize it has been distracted and may respond relatively early so as not to postpone the reinforcer. For two reasons, we reject this prediction. First, we hesitate to attribute complex metacognitive processes to animals. Second, human evidence shows that if a concurrent task demands attention, prospective duration judgment of a primary task is shortened, not lengthened (Brown et al., 1992; Brown & West, 1990; Macar et al., 1994).

Why have nearly all animal researchers failed to recognize the importance of attention to time? In the case of those proposing internal-clock models, the answer seems to be that they have failed to distinguish between general arousal and attentional resources (Kahneman, 1973). Proposing a separate role for attention in a modified version of a scalar-timing model has the advantage of parsimoniously accounting for some past findings. For example, Wilkie (1987) varied intensity of a 2-s or 10-s light cue in a choice response task. For equal durations of the dim light and the bright light, pigeons were more likely to choose the *short* response alternative following the dim light, as if the perceived duration of a dim light is shorter than that of a bright light of equal duration. Wilkie suggested that stimulus intensity affects the rate of the pacemaker, an explanation in terms of general arousal. The problem is that this explanation introduces the possibility that a wide variety of variables affect a process which most scalar-timing theorists assume is relatively autonomous, the process underlying the rate of the pacemaker. It is unlikely that the differences in intensity which Wilkie used would lead to different states of arousal, although Treisman (1993) also seemed to

assume such an effect. We propose another explanation: intensity of the light influenced the pigeons' allocation of attentional resources.

## Contextual-change model

The processes underlying prospective duration judgment differ from those underlying retrospective duration judgment (e.g., Block, 1992; Hicks, Miller, & Kinsbourne, 1976; Zakay, 1990; 1993).

## Prospective duration judgment

In the prospective paradigm, subjects are aware that they are engaged in a time-estimation task. All of the animal research and most of the human research on duration timing have used this paradigm.<sup>2</sup> In addition to duration length itself, the most important factor influencing prospective duration judgments is the amount of attention to time that the subject allocates during the duration. If, for example, a concurrent information-processing task is relatively easy, a subject can allocate more attentional resources to time, as opposed to stimulus information (see, for example, Block, 1992; Brown, 1985; Brown & Stubbs, 1992; Brown & West, 1990; Macar et al., 1994; Thomas & Cantor, 1975; Thomas & Weaver, 1975).

Block (1992) recently proposed a contextual-change hypothesis of prospective duration judgment. The most important kind of information influencing duration judgments is varied contextual associations, which may serve as time-tags. In the prospective paradigm, whenever a subject allocates attention to time, contextual information concerning the previous act of attending to time is automatically retrieved, and a new time-tag (set of contextual associations) is encoded. Prospective duration judgment involves estimating the availability of the changes in these time-tags, or temporal context changes.

With only a slight modification, the contextual-change model can be seen as functionally isomorphic with the attentional-gate model developed in the previous section. Figure 7 (p. 186) shows the relabeling of components illustrating this isomorphism. The pacemaker becomes the *context generator*, the cognitive timer becomes the *context recorder*, and the cognitive comparison process becomes the *context comparison* process. The labels for other components remain the same. One major difference is that the contextual information produced by the context generator is not equivalent from moment to moment, at least not in the way that each pulse is assumed to be identical to every other pulse. The

<sup>2</sup> However, see Zimmer, this volume, chapter 3



context comparison process may rely on the total number of unique contextual associations that were encoded during the duration and that are available to a memory retrieval process (cf. Block, 1992). The main advantage of this model over the attentional-gate model is that it reveals more explicit connections with other temporal judgment tasks. For example, judgments of the recency or serial position of an event, as well as the spacing of repeated or related events, seem to depend on contextual associations (Hintzman et al., 1973; Hintzman et al., 1975).

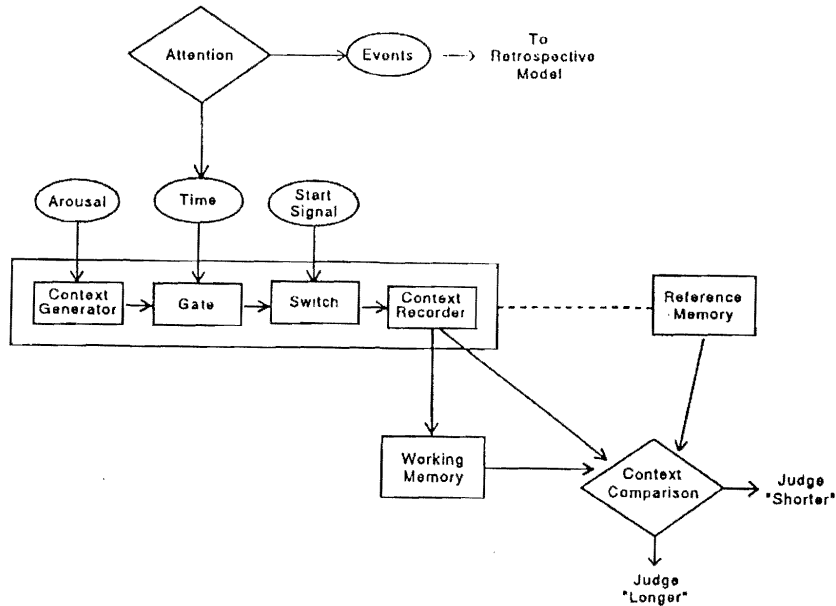


Figure 7: The contextual-change hypothesis of prospective duration judgment diagrammed as a model (after Block, 1992).

### Retrospective duration judgment

In contrast to the paradigms we have already discussed, in a retrospective duration-judgment paradigm the person is not aware until after a duration has ended that the situation requires a duration judgment. This is a difficult, if not impossible, paradigm to use in nonhuman animal studies (Wearden & Lejeune, 1993). We cannot easily give animals a short verbal instruction, following a duration, to make a retrospective judgment of the duration. The required training would introduce a lengthy delay between the duration and the animal's judgment. We can ask humans, however, to make such a judgment. Attention to time has little or no influence on retrospective duration judgment. Retrospective

judgments do not depend so much on retrieval of temporal context information as on retrieval of other kinds contextual information. This contextual information is encoded in association with event information. It includes environmental, emotional, process, and other similar information. Block (1982; 1985; 1990; 1992; Block & Reed, 1978) proposed a contextual-change hypothesis of retrospective duration judgment, or remembered duration. The remembered duration of a time period lengthens as a function of the amount of contextual changes stored in memory and available to be retrieved at the time of the duration judgment.

Figure 8 (p. 187) shows the components of the attentional-gate model (Figure 6, p. 182) or the contextual-change model of prospective duration judgment (Figure 7, p. 186) needed in a model of retrospective duration judgment. The main focus is on associations formed, mostly automatically, as a subject attends to events (internal or external). The context generator supplies contextual information, which is associated with *event* information and stored in *long-term episodic memory*.

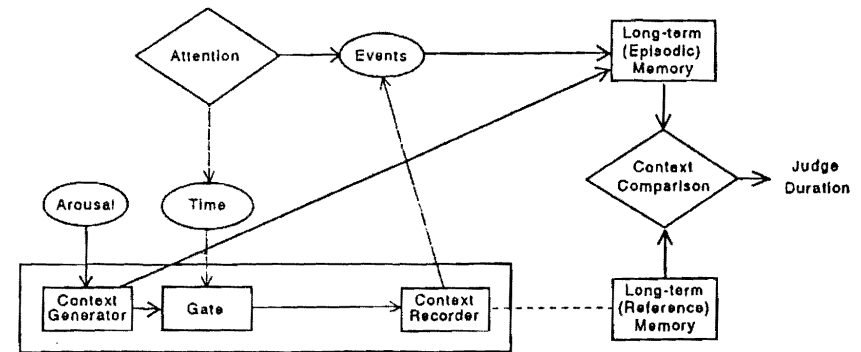


Figure 8: The contextual-change hypothesis of retrospective duration judgment diagrammed as a model (after Block, 1992; Block & Reed, 1978).

Even in a retrospective paradigm, the subject occasionally attends to time. On these relatively rare occasions, the *context recorder* holds information about contextual changes and supplies this information, again in the form of an association to concurrent events. Information about contextual changes is also sent to a *long-term reference memory*. This component holds information about the average amount of unique contextual information stored during durations of various length. In other words, it contains information about the translation from contextual information into duration judgments (expressed verbally or otherwise). Retrospective duration judgments involve a *context comparison*

involving this information in long-term episodic memory and in long-term reference memory.

## Biopsychological evidence

A variety of biopsychological evidence from both animal and human experiments relates to the kinds of models discussed and proposed here (Block, 1995; Church, 1989). This evidence allows a tentative separation of brain modules or areas subserving the timer from those subserving memory, as well as attentional processes.

Functioning of the internal clock or cognitive timer seems to rely mainly on the frontal lobes of the cerebrum, especially the dorsolateral prefrontal cortex. Converging evidence from psychopharmacological manipulations, electrophysiological recordings, and neuropsychological observations seemingly isolates the timer to this brain region. Researchers who have administered various drugs to animals trained on FI (i.e., peak procedure) and DRL schedules suggest that dopaminergic neurons, which the prefrontal cortex is known to contain, subserve the timer. For example, administering methamphetamine leads to a peak-shift left, as if the animal expected reinforcement sooner. The typical interpretation is that the rate of a neural pacemaker has increased, thereby leading to a greater accumulation of pulses in working memory. Administering dopamine antagonists, such as haloperidol (which blocks postsynaptic dopamine receptors), conversely leads to a peak-shift right. Single-cell recording from neurons in the prefrontal cortex reveals some that are active in the interval between the onset of a stimulus and the time an organism may emit a response (for reviews, see Fuster, 1987; 1989). In humans, damage to this region of the prefrontal cortex disrupts various timing functions, including discriminating the recency and temporal order of events (Milner et al., 1985; 1990; 1991). However, none of this evidence shows that it is necessary to postulate an autonomously functioning, repetitive pacemaker as the first component in duration timing, such as in several models we have discussed here (Figure 3, p. 176, Figure 4, p. 177, and Figure 6, p. 182). As Milner et al. (1990) argue, the evidence may be more consistent with the notion that the dorsolateral prefrontal cortex automatically generates contextual information which may serve as time tags (Figure 7, p. 186, and Figure 8, p. 187).

Other evidence reveals that other brain regions mediate reference memory for temporal (duration) information. The hippocampus and associated medial temporal lobe structures are influenced by cholinergic agonists and antagonists. Administering drugs that influence cholinergic neurons shortens or lengthens the remembered duration of a time period.

For example, anticholinesterases (e.g., physostigmine) and cholinergic receptor blockers (e.g., atropine) influence rats' performance in the peak procedure in ways that scalar timing theory can elegantly handle (Church, 1989; Meck & Church, 1987): The pacemaker rate ( $\Lambda$ ) does not change, but the memory storage constant ( $K^*$ ) does. The parameter  $K^*$  is a bias on the transfer of pulses from the accumulator to reference memory, and the value of  $K^*$  may be greater or less than 1 depending on such influences as cholinergic drugs. In humans, the remembered duration of a time period is shortened or lengthened in similar ways (Hicks, 1992). Studies of individuals with damage to the medial temporal lobe, especially the hippocampus, provide converging evidence that this brain region is intimately involved in reference memory functions (Block, 1995).

Exactly which areas of the brain subserve attention to time remains unclear. Studies using positron emission tomography reveal that several anatomically separate areas of the human brain, including the thalamus, the parietal lobes, and the anterior cingulate gyrus, play various roles in the performance of attention-demanding tasks (for a review, see Posner & Raichle, 1994). These areas subserve somewhat different functions, which are just beginning to be clarified. The likely candidate for an area subserving the allocation of attention to external events or to time (as in the models shown in Figure 5, p. 181, Figure 6, p. 182, Figure 7, p. 186, and Figure 8, p. 187) is the anterior cingulate gyrus. This area seems to be the central component of an executive attention network, which may directly influence the working-memory functions of the dorsolateral prefrontal cortex. However, the present evidence is too incomplete to suggest anything more definitive about brain components subserving the role of attention in the cognitive models of time we have reviewed and proposed here.

## Summary and conclusions

Timing-with-a-timer models assert that a pacemaker, part of an internal clock, underlies psychological timing. Timing-without-a-timer models propose instead that psychological time is constructed from processed and stored information. The scalar-timing model, the best example of timing with a timer, can explain much of the animal data and some of the human data on time-related behavior and judgment. However, it is not easily able to explain why cognitive factors influence temporal behavior and judgment. In order to handle these factors, we proposed a modified model that incorporates an attentional process. This model, the attentional-gate model, is needed to explain findings in which

humans divide attention between temporal and nontemporal information. It also explains and predicts some analogous findings in animal research.

The attentional-gate model is roughly isomorphic with a contextual-change model of prospective duration judgment. This model, which involves timing without a timer; replaces the pacemaker mechanism with a process that generates varied contextual information. Temporal context changes, stored as contextual associations with ongoing events, may therefore underlie prospective duration judgments. A modification of this model can also explain retrospective duration judgments, which are more typically explained by proposing cognitive models.

Biopsychological evidence from both animal and human experiments relates to the models reviewed. The areas of the brain that are heavily implicated in various aspects of time-related behavior and judgment include the dorsolateral prefrontal cortex, the anterior cingulate gyrus, and the hippocampus. At present, biopsychological evidence does not unequivocally lead to acceptance or outright rejection of any of the models reviewed here. Future research, using or combining behavioral, cognitive, and biopsychological methods, may clarify the processes underlying time-related behavior and judgment in animals and humans.

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ERRATUM: Figures 2 and 3 were transposed in the book. In this reprint, they have been put in their proper locations on pages 175 and 176.