Origins and development of internal clock theories of time

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Abstract

The article describes the origins and development of internal clock theory. The history is traced via body temperature studies in the 1920s and 1930s, with input from 19th. century and early 20th. century psychophysics, through to the landmark model of Treisman (1963). This model derived timed behaviour from an interaction of internal clock, memory store, and comparison processes. A successor to Treisman's model was the *scalar expectancy theory* (SET) of Gibbon and colleagues (1984). The origins of SET in animal Psychology are described, as is its application to human timing (in the early 1990s), in particular recent work on the operation of the internal clock itself. Finally, a discussion of some recent developmental studies of timing illustrates both how internal clock models have been applied, and how modern research may require a reconceptualization of the operation of classical internal clock models.

The purpose of the present article is to trace the origins of, and developments in, what has been the most popular approach to the psychology of time perception, internal clock theory. The article is intended as an introduction for the general (but psychologically-trained) reader, and as such will concentrate on what seem to me to be the principal important *ideas* of internal clock theory, rather than the technicalities of experimental methods or the minutiae of theoretical details.

The basic structure of the article is as follows. I begin with a discussion of the historical roots of internal clock theory, mainly involving the development of the idea of a "chemical clock" in the 1920s and 1930s. Following on from this, I discuss the two most influential internal-clock-based models, those of Treisman (1963) and Gibbon, Church, and Meck (1984). Although these two theories are similar, they have different origins: the first from "chemical clock" theory and psychophysics, the second from animal conditioning studies, and I will briefly review the influence of animal research on the development of internal clock theory.

Later sections of the article will discuss the application of internal clock models to humans, and show how human research has tested the operations of the proposed theoretical mechanisms of such models. In addition, I will also show how some very recent research has applied internal clock models to long-standing problems in time Psychology, such as developmental changes in time experience and behaviour.

To provide a coherent discussion of some historical and recent issues within a short article requires some restriction of content. I have restricted the material discussed here in two main ways. Firstly, I will discuss only internal-clock models, and not other approaches to time perception. Droit-Volet and Wearden (2003) provide a recent review not only of some of the models discussed in the present article but also, more importantly, their competitors, which involve mechanisms other than the internal clock, and the reader is referred to this other article for information on these. A second restriction is that the work I will review refers only to data collected within "prospective timing" paradigms.

The classical timing literature (as reviewed by Fraisse, 1964, for example), although distinguishing carefully between the different methods used to obtain time judgements, pre-dated the distinction between *prospective* and *retrospective* time judgements, which has now become standard in the field (Hicks, 1992). Prospective time judgements are obtained when people are told in advance that a time judgement is an essential feature of the task (e.g. "hold down this button for 1 second", "listen to these two tones and tell me which lasts longer"). Because of the lengthy training needed to establish behaviour, all timing tasks using animals are also considered to be prospective. In contrast, retrospective judgements come from tasks where people are asked unexpected questions about time (e.g. "how much time has passed since you started reading this paragraph?").

Most theorists consider prospective and retrospective timing to be performed by different psychological mechanisms: the former by some sort of dedicated timing process (such as a clock), the other on the basis of more general cognitive information processing not specifically related to time. This distinction has been instantiated in the often-quoted distinction between "timing-with-a timer" (prospective timing) and "timing-without-a -timer" (retrospective timing), see Block (2003) and Ivry and Hazeltine (1992) for discussion. Given that the focus of the present article is on the origins and development of internal clock theory, I will only discuss data and theories relevant to prospective timing.

Figure 1 about here

Internal clock theory: Origins

The idea of an internal clock, which was to reach its fullest expressions in the models of Treisman (1963) and Gibbon, Church, and Meck (1984), was prefigured by research in the 1920s and 1930s, and even relates to work conducted in the 19th. century.

François (1927) deserves historical priority for his research on body temperature and time estimation, although English-speaking Psychology usually awards credit for publicizing the idea to Hoagland (1933, 1935). Hoagland initially became interested in this area when his wife was ill with influenza, and he noticed that she "was impressed by the fact that time seemed to pass very slowly" (Hoagland, 1935, p. 108). To test whether his wife's subjective time had been changed, Hoagland asked her repeatedly to count up to 60 at an estimated rate of 1 count/second, and noted how long she took when her body temperature had different values. Figure 1 shows the average values his wife produced. Not only did Mrs. Hoagland count faster when her temperature was elevated, but the data show evidence of a parametric effect, with higher temperatures producing systematically faster counts, up until the highest where, presumably, the illness had a partly debilitating effect.

In terms of the passage of subjective time, Mrs. Hoagland's shorter interval productions at higher temperatures are evidence that her internal timing mechanism ran faster when her temperature was higher. Body temperature increases would make productions shorter, although they would make external events seem to last longer, accounting for the subjective effects of body temperature that Hoagland's wife experienced. In terms of theoretical explanation, Hoagland reasoned that if some underlying chemical process provides "ticks" for a time estimation mechanism, then like any chemical process it will run faster when heated and slower when cooled. The relation between the rate of a chemical reaction and temperature is governed by an equation proposed by Arrhenius in 1880, where a critical parameter is the "energy of activation" or "temperature characteristic" of the reaction, and . Hoagland took the chemical clock hypothesis sufficiently literally to attempt to actually measure this parameter from time judgement data.

Some years before Hoagland's work, François (1927) had used the technique of diathermy (the passage of high-frequency electric current through the body) to increase body temperature, and observed effects on various time judgement tasks when compared with an unheated control condition. Hoagland later became aware of Francois's work, and used data from François's earlier study, combined with his own, to calculate the energy of activation of the "chemical clock". Francois's data and Hoagland's were well described by the same energy of activation, leading Hoagland to conclude that the results from the different types of body temperature manipulation "definitely imply the existence of a unitary chemical process serving as a basis for the subjective time scale…" (Hoagland, 1935, pp. 111-112). Others, however, have been more sceptical, and Bell (1966) reported different energy of activation values from his own studies, suggesting that more than one underlying process was controlling timing. With historical hindsight, estimating the parameters of a fundamental equation of physical chemistry from the data obtained in psychological experiments seems a highly ambitious enterprise, but the general idea that if a physical manipulation can alter time perception, some physical mechanism must underlie it has been influential even in the present day, as will be seen later.

Wearden and Penton-Voak (1995) reviewed data from almost all the small number of studies which have used body temperature manipulations to try to change time judgements. Various methods have been used (heated rooms, heated helmets, water baths, both hot and cold, diathermy, and even natural fevers, as in Alderson's, 1974, replication of Hoagland, 1933). Wearden and Penton-Voak (1995) converted the data from the various studies into a single scale, one which related the rate of passage of subjective time to body temperature. All studies reported had some sort of control condition where body temperature was normal, so increases and decreases in body temperature could be related to increases and decreases in the rate of passage of time. In general, strong relations were found between these two variables: almost all studies where body temperature had been elevated found increased rates of passage of time, and the (much rarer) studies where temperature had been reduced found reduced rates of passage of time. The conclusions, however, depended on separating out prospective and retrospective time judgements, which earlier studies had usually failed to distinguish. No effect of body temperature on time judgements that were certainly, or probably, retrospective was found.

As mentioned above, the fact that a physical manipulation can alter subjective time is *prima facie* evidence for the existence of some temperature-sensitive internal clock, but early workers had little concern for the exact mechanics of such a clock, such as how it operates, how its readings are used as the basis for time judgements, and so on. For such developments, we have to wait until the 1960s.

Some other influences on time Psychology that manifested themselves in the 1960s and later came from 19th century time psychophysics (see Fraisse, 1964, p. 8, and chapter 5, pp. 116-147). Among the issues raised were the question of the relative variability of time judgements (i.e. the question of conformity to Weber’s law, discussed below), the possible existence of an “indifference interval” where durations were more accurately perceived than at shorter or longer values, and the question of whether the type of event judged (e.g. stimulus modality) played a critical role in duration judgements. Some of these issues will be discussed in more detail later in the present article, but for the moment it is sufficient to note that the data obtained gave time Psychology a quantitative “flavour”, which it has since the 1960s. That is, most current models of prospective timing attempt to provide quantitatively exact accounts of the phenomena they treat, either by using mathematical analysis or computer simulation.

Of the several preoccupations of classical psychophysics, the most important one from the point of view of later internal clock theory was *Weber's law*. In its original form, Weber's law relates measures of variability of a judged quantity to its mean, so for example, on timing tasks, the standard deviation of estimates of some sort would be related to the mean estimate. There are various ways of examining conformity to Weber's law in timing. One is to measure both the mean and standard deviation of time judgements and examine their relations. For Weber's law to hold, the standard deviation should increase linearly with the mean. Another method is to express the standard deviation as some fraction of the mean (or time to be judged), and conformity is indicated by the fraction remaining constant as the interval to be timed varies. Yet another method is to divide the standard deviation by the mean to produce a coefficient of variation or Weber fraction. For Weber's law to hold, this quantity should remain constant as the interval to be timed varies.

Weber's law in timing implies a mechanism with constant sensitivity as the interval to be timed changes so, although longer times might be timed with greater variability (in the form of larger standard deviations) than shorter ones, they are not *relatively* more variable. As will be seen later, a large amount of evidence relating to internal clock theory is consistent with the application of Weber's law to timing.

Treisman (1963)

In 1963, Michel Treisman produced what everyone would agree is a landmark in the development of internal clock theory. Treisman (p. 18) modestly writes that his model “derives from suggestions which have been made before…and attempts to put them together in not too arbitrary a fashion….” , but in fact his model was so sophisticated and advanced for its time that it was only equalled, but perhaps not even surpassed, by the rather similar proposal of Gibbon et al. (1984) that dominates many studies of time perception even now. In his article, Treisman linked his work specifically to the "chemical clock" proposition of Hoagland (1933), and to 20th. century psychophysics (e.g. Woodrow, 1930), but his development goes well beyond what was prefigured in these earlier studies.

Figure 2 about here

The upper part of Figure 2 shows an outline of Treisman’s model. The raw material for time judgements comes from an arousal-sensitive pacemaker, which sends pulses to a counter. The pulses are assumed to be periodic. As well as the pacemaker and counter, the model also involves a store of "reference" durations, and a comparator mechanism. Comparison of values in the counter and the store determine behavioural output.

Treisman's model contains the basic mechanism of a pacemaker-accumulator clock (pacemaker-counter), which was later used by Gibbon et al. (1984), but also shows that in order to generate any kind of timing "behaviour" then more than the basic clock mechanism is needed, with both some kind of store of reference times and, most importantly, some comparison mechanism also intervening in any time judgement. Treisman's work thus situates a simple clock mechanism within the framework of a more complex cognitive system involving both memory (store) and decision (comparator) mechanisms.

To illustrate in general how the mechanism might work, consider a task of temporal reproduction, such as used by Woodrow (1930). In this study, people received examples of "reference" durations, in the form of the time between two taps produced by a mechanical device. The time intervals ranged from 200 msec up to 30 seconds. The subject's task was to make two taps with the same inter-tap as interval as the reference duration. Treisman's model would place the number of ticks corresponding to the reference durations in the store, then the interval reproduced would be terminated when the number of ticks accumulated in the count mechanism was judged to be equal to that retrieved from the store for the duration of interest, with the judgement being made by the comparator. Treisman's model also incorporated sources of variance and error in pulse accumulation, so that durations were not necessarily reproduced accurately, nor were they invariant from one trial to the next. For a detailed mathematical account of the operation of Treisman's model see his pages 19-21.

One of the enduring mysteries of time Psychology is why publication of Treisman's article failed to produce an immediate flowering of interest in time perception. Many of the possible explanations for the apparent lack of impact of this article, now recognized as possibly *the* classic work of time

Psychology, do not seem to apply. For one thing, the work was published, not in some obscure journal, but as a monograph supplement to *Journal of Experimental Psychology*, considered then, as now, one of the premier outlets for experimental research. For another, although the work had some mathematical aspects, it was not particularly obscure or difficult to understand. However, the neglect of Treisman's achievement was almost immediate, as his work was not referred to in the text of Cohen's (1964) popularization of some research in time Psychology published in *Scientific American* just after the publication of Treisman's article, nor was it referenced for further reading. On the other hand, Treisman's own account of his work in a "popular science" publication (Treisman, 1965) cited Cohen (1964), but this simple account of his model did not appear to lead to widespread interest in it.

Perhaps the main reason why Treisman's work did not achieve the revolution in the study of the subject that might be imagined is that the body of data to which is was applicable was at the time small, and seemed peripheral to the important concerns of Psychology in the 1960s, such as attention and memory. For example, the study by Woodrow (1930) to which Treisman made much reference in his 1963 article, was not only old at the time of Treisman's writing, but also involved only a single experiment, with different parts having either 8 or 5 subjects, and involving the reproduction of 15 time intervals, albeit in a complex and rigorous experimental design. Thus one might say that the model was an elegant and advanced solution to questions which were not at the time thought to be important problems: perhaps the model lacked impact not because it was not a good *theory*, but because of weaknesses in, or paucity of, *data*. However, a later model, which bears a striking resemblance to that of Treisman, did have a body of data to support and test its predictions.

Animal Psychology and the development of scalar expectancy theory (SET)

At the end of the 1970s and the beginning of the 1980s, the late John Gibbon along with colleagues, notably Russell Church and Warren Meck, who have both made extensive independent contributions to the Psychology of time developed *scalar expectancy theory* (SET), an outline of which is shown in the lower part of Figure 2. The resemblance to Treisman's 1963 model is striking: both models share (a) a pacemaker-counter/accumulator mechanism (b) a "store" or "reference memory" and (c) a comparison process on the results of which behavioural output is based. There are a number of small technical differences between the models, but perhaps the most historically-important difference between the two models resides not in their structure but in their domains of application. Treisman's 1963 model dealt mainly with a small amount of data from psychophysical experiments collected by Treisman himself and a few other workers, whereas SET attempted to explain a much larger body of data, that coming from research on timing in animals such as rats and pigeons.

The fact that the behaviour of animals could be sensitive to temporal properties of experimental events was known from at least the time of Pavlov. In his *inhibition of delay* paradigm, Pavlov used very long conditioned stimuli, and found that, after considerable training, the salivation to the stimulus showed temporal regulation in that it was absent early in the stimulus, but became progressively more likely as the usual time of food delivery approached. However, the study of animal timing received its greatest impetus from the development of the technique of *operant conditioning* by Skinner (1938).

In the usual operant conditioning paradigms, animals like rats and pigeons make operant responses (lever-presses or key-pecks) which are rewarded with food according to schedules of reinforcement. These schedules are contingencies imposed by the experimenter which relate aspects of operant responding to the delivery of food. Skinner (1938) developed one particularly useful technique, the *fixed-interval* (FI) schedule of reinforcement. On FI, the first response occurring t seconds after the previous food delivery is itself rewarded so, effectively, reward deliveries are delivered with almost exact temporal periodicity. On FI, the normal result is that responding on average accelerates throughout the interval, being absent or at very low levels immediately after food delivery, and progressively increasing as the time since food increases, reaching a maximum at or near the time of the next food delivery.

A wide range of animal species exhibits temporally-regulated behaviour on FI: Lejeune and Wearden (1991) discuss data from animals as diverse as turtles, fish, cats, and primates. The patterns of behaviour shown on FI can be quantitatively analyzed, and used to test theories of timing. In a slightly simplified form, the SET system explains FI performance as follows. Suppose the normal time between food deliveries is *t* seconds. This interval is learned by the animal and stored in reference memory. During any particular interval, the animal's internal clock measures elapsing time from food delivery, and this time accumulates in the accumulator or working memory. The time elapsed in the interval is compared with the "reference" time (i.e. the learned interval value), and if the two are "close enough", according to some comparison process, then the animal emits a response, otherwise it does nothing. Church, Meck, and Gibbon (1984) give a more rigorous account of how SET explains behaviour on FI-like schedules. However, the parallels between SET's explanation of animal performance and Treisman's explanations of data from humans are obvious.

As well as FI, a large body of other work had exposed animals to contingencies involving temporal constraints (see Gibbon, 1991, for discussion) and an extensive and orderly database existed which both required theoretical explanation (which SET tried to provide), and could serve as a test-bed for theoretical development. Thus, advantages that SET had over Treisman's model were (a) that the problems of animal timing were considered "mainstream", at least in the animal learning field, so influential in U.S. Psychology via its link to behaviourism and (b) that a large body of well-known but unexplained data existed for timing models like SET to work on.

As Gibbon (1991) points out in his discussion of the origins of SET, he was particularly impressed by one notable feature of many observations from animal timing experiments. This was a sort of "proportional timing", where measures of behaviour seemed to adjust to the *proportions* of time intervals, rather than their absolute values. An example of this which particularly influenced Gibbon came from Dews (1970), whose data were reproduced by Gibbon (1991) in his Figure 1 (p. 5). Dews (1970) trained pigeons on FI values of 30, 300, and 3000 seconds, and found that, if response rate during successive fifths of the FI value was plotted as a fraction of the rate at the end of the interval, the resulting functions looked the same: for example, half way through an FI value, the response rate is the same fraction of what it will be at the end, regardless of the absolute duration timed.

Another striking expression of "proportional timing" in data from animals, this time relating to variability in behaviour rather than mean, came from Church and Gibbon's (1982) experiment on temporal generalization. To simplify slightly, rats were initially rewarded for pressing a lever after a stimulus of some duration (e.g. 4 seconds), but were not rewarded for presses after shorter or longer stimuli. The rats then received testing with a range of stimulus durations (less than, equal to, or greater than 4 seconds) and the resulting probability of lever-pressing was plotted against stimulusduration. This resulted in a "temporal generalization gradient" which resembled a Gaussian function centred on 4 seconds, and declined symmetrically as values deviated from 4 seconds. When other reference durations were used (2, and 8 seconds), Church and Gibbon found that the generalization gradients superimposed when plotted on the same relative scale (with each presented duration being expressed as a fraction of the reference value for that condition), again suggesting a kind of "proportional timing"; that is, animals confused a duration with the standard when it differed by a certain *proportion* of the standard, not when it differed by a certain absolute amount (e.g. see also Gibbon's, 1991, discussion of behaviour on some avoidance procedures for other examples of "proportional timing").

Yet another example cited by Gibbon (1990) as having influenced his thinking comes from an experiment by Catania (1970) which tested pigeons on something close to a human psychophysical procedure. A response key was illuminated, and pigeons were rewarded for a single key-peck, but only if this occurred more than *t* seconds after illumination of the key. A peck before this time was not rewarded, and led to an inter-trial interval before another trial occurred. Thus, the animal was rewarded if it "waited" at least *t* seconds before responding. Of particular interest to Gibbon was the variability of performance on this task as a function of the mean "wait time". Catania (1970) showed that this wait time obeyed Weber's law in that the standard deviation of the wait times was a constant proportion of the mean time, as the produced wait time varied, essentially a form of Weber's law applied to animal timing (see the lower panel of the present Figure 3). For other examples of data of this sort see Platt (1979).

This proportional timing was the basis of the term "scalar" in SET, where the general idea is that the timing of absolutely different intervals can be showed to be the same when plotted on the same relative *scale*, that is when all time values are expressed as a fraction of some "important" time, such as a time associated with reward.

The use of animal subjects in studies related to SET in the 1970s and 1980s enabled the observation of radical pharmacological effects, impossible to obtain in humans. For example, Meck (1983) showed (a) that drugs that stimulated the dopamine system of the brain appeared to change the speed of the pacemaker of the internal clock, speeding it up when dopamine levels were elevated and slowing it down when dopamine levels were reduced, and (b) that cholinergic drugs systematically affected temporal memory processes rather than clock processes, making rats remember the time at which food was delivered as being shorter or longer than it really was. The success of such pharmacological manipulations, like the earlier effect of physical manipulations such as body temperature, suggested that the internal clock was a real physical mechanism. In addition, of course, the pharmacological separation of clock and memory processes suggested that these components of the theory were different in reality, and not just different parts of a psychological model. For a general review of pharmacological effects on animal timing, see Meck (1996).

Application of internal clock models to humans and the speed of the internal clock

The idea that SET might be used to explain timing in humans surfaced occasionally in literature during the 1980s (e.g. Zeiler, Scott, & Hoyert, 1987), but Wearden and McShane (1988) were probably the first to explicitly use SET-related ideas in a discussion of human timing. Wearden and McShane asked participants to produce time intervals ranging from 500 to 1300 msec, values too short to make counting useful. The mean time produced tracked the required time almost perfectly (a form of "proportional timing", although in this case the proportion was 1.0), and the property of superimposition was present in the data.

However, similarities between timing data in humans and animals had long been potentially detectable in the literature, and Figure 3 shows one previously-unnoticed parallel, using data from Woodrow (1930) and Catania (1970), both articles which were influential in the development of Treisman's (1963) model, and SET (Gibbon et al., 1984), respectively.

Figure 3 about here

In Figure 3, the two tasks are reproduction of time intervals ranging from 0.2 to 1.5 seconds (Woodrow, 1930), and reinforcement of "wait times" in pigeons, which ranged from 1.27 to 24.4 seconds. The measure shown in Figure 3 is the standard deviation of the reproductions, or wait times, expressed as a fraction of either the interval to be reproduced (Woodrow), or the wait time produced (Catania). The plot shows that the standard deviation remained at almost exactly the same percentage of the interval timed, as the duration to be timed varied markedly. These data show a form of conformity to Weber's law, a hallmark of SET. The value of the percentages shows that timing was relatively less variable in the data from humans than animals, something that was also shown in other work later (e.g. Wearden, 1991a, Figure 1, p. 61).

The success of SET quickly led to the development of what Wearden (1991a) called "analogue" experiments, experiments designed for humans, but inspired by methods used with animals, and which produced data that was related to SET in animal studies. The two most popular were temporal generalization (derived by Wearden, 1991a, 1992, from an animal experiment by Church & Gibbon, 1982), and temporal bisection (derived, independently, by Allan & Gibbon, 1991, and Wearden, 1991b, from an animal experiment by Church and DeLuty, 1977).

There were two advantages of analogue experiments. The first was that the questions that they posed to the subjects were necessarily simple (such as whether or not two stimuli had the same duration), so could be used not only with adults, but also with children who might find complex instructions difficult to follow and maybe have no knowledge of conventional time units such as seconds, as will be seen later. The second advantage was that the theoretical analyses of performance on animal timing tasks which had been a cornerstone of SET could be used, albeit sometimes in an adapted form, to explain human performance. However, as will be discussed later, the use of animal-based models to explain human performance also brought with it certain assumptions which might not be valid.

The success of SET as an account of human performance on some timing tasks (reviewed by Allan, 1998) also breathed new life into the old idea of François (1927) and Hoagland (1933), that humans might possess an "internal clock". A particular focus of interest, both in "animal" SET and its application to humans, has been attempts to change the rate of the pacemaker of the internal clock, usually to increase it, a manipulation often referred to casually as "speeding up the clock".

Studies working within the framework of "animal" SET had apparently sped up the clock using amphetamine (Maricq, Roberts, & Church, 1981; Meck, 1983), and the much earlier work on body temperature effects in humans (Wearden & Penton-Voak, 1995) obviously had this same aim. Treisman, who had contributed only sporadically to the field of time

Psychology since his landmark 1963 article, although he was prominent in other areas of experimental Psychology, made a second highly-significant contribution in 1990, with the publication of an article that provided an innocuous method of speeding up the pacemaker of the internal clock in humans.

Treisman, Faulkner, Naish, and Brogan (1990), as part of a study which actually focussed on something slightly different, reported that if a stimulus was accompanied by a train of repetitive stimulation (periodic clicks or flashes) people behaved as if the duration of the stimulus had increased, compared with a control condition. The periodic stimulation was supposed, among other effects not relevant to the present discussion, to produce an increase in "arousal" and such an increase, consistent with Treisman's model outlined in Figure 2, would lead to a higher pacemaker rate.

Several studies have used repetitive stimulation to "speed up" the pacemaker of the internal clock in humans. Penton-Voak, Edwards, Percival. and Wearden (1996) showed that preceding an auditory or visual stimulus by 5 seconds of periodic clicks made the stimulus seem to last longer (see also Wearden et al., 1998, and Wearden et al., 1999a, for replications) whereas when people were required to *produce* time intervals of specified durations, preceding the productions by clicks made the productions shorter (see also Burle & Bonnet, 1997, 1999; Burle & Casini, 2001, for replications). The different effects on the subjective estimate of stimulus durations and intervals produced by a "speeding up the clock" manipulation are exactly in accord with internal clock theory. If people are making time judgements on the basis of the number of "ticks" of the internal clock, then more ticks will accumulate per unit time when a stimulus is presented if the clock is speeded up, compared with a "normal" control condition, thus making it appear longer in duration. On the other hand, if production tasks are performed by emitting responses when a certain number of ticks have been accumulated (see Wearden, 2003, for a reproduction model of this sort), then these ticks will be accumulated in a shorter real time with the "speeded up" clock, thus shortening the times produced.

If the clock can be speeded up, can it also be slowed down? Wearden, Philpott, and Win (1999a) showed that it could, at least relatively. To simplify their study slightly, people learned standards either with a "normal" clock or with a "speeded up" one, then had to make judgements about the durations of comparison stimuli timed with a "normal" clock. People behaved as if the durations presented were relatively shorter in the "normal" condition compared with that when the standards had been learned, indicating a relative slowing down of the internal clock.

In another experiment of this sort, Droit-Volet and Wearden (2002) used repetitive flicker to speed up the pacemaker of the putative internal clock of children as young as 3 years of age, and found that this manipulation changed behaviour in a way compatible with a change of pacemaker speed. All these experiments together suggest that humans as young as 3 behave as if they have a pacemaker-accumulator clock of the type proposed by Treisman's 1963 model and by SET.

However, although there is evidence that repetitive stimulation in the form of clicks and flicker will increase internal clock speed in the manner proposed by Treisman et al. (1990) is there any evidence that the effects are mediated by "arousal"? A train of clicks is obviously not very arousing in the normal sense of the word, although it may induce "specific arousal" of the internal clock, but there is a small amount of evidence that the pacemaker of the internal clock is sensitive to arousal as this term is normally understood. Some comes from Treisman (1963), where, in his experiment 3, people were required to produce or reproduce intervals of either 0.5 seconds or 3 seconds. The intensity of tone stimuli presented in the experiment varied over values of 20, 50, and 80 decibels, and in the 0.5 second conditions, the durations produced and reproduced were consistently shorter the greater the intensity of the tone, although there were no effects when the durations to be produced or reproduced were 3 seconds. Treisman (1963) interpreted this effect as due to the increased arousal of the subjects occasioned by the louder tones.

In a much more recent study, Wearden, Pilkington, and Carter (1999b) examined the effect of *decreases* in arousal during an experimental session. The method used was a variant of temporal generalization (Wearden, 1992). Here, subjects were initially presented with a standard stimulus duration (in the case discussed, Wearden et al, 1999b, Experiment 3, this was a light-blue square presented on a computer screen for 400 msec), then received other comparison stimulus durations (ranging from 100 to 700 msec) and had to judge whether or not or each comparison had the same duration as the standard. The usual temporal generalization method (e.g. Wearden, 1992) gives feedback after the response to each comparison, telling subjects whether or not their response was correct, but none of the studies in Wearden et al. (1999b) did this.

A peculiarity of the data in Wearden et al. (1999b) was that, as the experimental session progressed, the comparison duration that was maximally identified as the standard got longer and longer. Wearden et al. reasoned that this was because arousal was falling as the (very boring) experiment progressed, so the pacemaker of the internal clock was running more and more slowly. Suppose that a person represents the duration of the standard by *n* "ticks" of the clock (i.e. this is the reference value in SET's "reference memory" or Treisman's "store") then, as the pacemaker rate slows, longer duration stimuli are needed to accumulate these *n* ticks, so longer and longer durations are identified as the standard.

A common problem in attributing changes in behaviour to changes in arousal is that no independent measures of arousal are usually taken in the experiment, but Wearden et al.,'s experiment 3 actually used an arousal rating scale, and found that, as they had predicted, the shift in the choice of comparison durations as the experiment progressed was accompanied by a decrease in reported arousal.

Another area where internal clock theories have recently made an important contribution is the problem of why "sounds are judged longer than lights" (that is, why auditory stimuli have longer perceived durations than visual stimuli of the same length). Wearden, Fakhri, Edwards, and Percival (1998), and Droit-Volet, Tourret, and Wearden (in press) used the idea that the pacemaker of the internal clock runs faster for auditory than visual stimuli to account for this result, and showed that the data were consistent with the quantitative predictions of different pacemaker speeds for the two modalities. The latter experiment also provided the first demonstration of the "sounds/lights" effect with children.

Overall, therefore, some recent research, consistent with the general framework provided by both Treisman's original (1963) model and SET, supports the idea that humans possess an internal clock of the pacemaker-accumulator type. The rate of this pacemaker can certainly be influenced by repetitive stimulation, as Treisman et al (1990) proposed, but the exact mechanism by which this occurs remains rather mysterious. Some work concurs with Treisman's (1963) contention that the pacemaker is sensitive to the arousal level of the subject, although convincing manipulations of arousal (when the term is used in its everyday sense) remain rare.

Developing human SET: Developmental studies and the mechanics of internal clock models

As mentioned above, "human" SET has revived interest in internal clocks as an explanation of human time perception, and has provided methods which have been extensively used with humans (see Elevevag et al., 2003, for recent application to timing in people with schizophrenia). Another recent area of research has been the use of SET-compatible models (that is, models based on the clock/memory/decision mechanisms of SET) to try to account for performance on classical timing tasks such as temporal reproduction (Wearden, 2003).

However, perhaps the most interesting and influential area has been the application of internal-clock-based models to developmental issues in timing, such as timing in children and the elderly. A complete review is given in Droit-Volet (2003), but my focus here is on how internal clock models are used to interpret developmental differences in timing behaviour, why the explanations have the form that they have, and what the explanations tell us about the operation of internal clock theories.

To illustrate these points, I will concentration only on developmental data collected using a temporal generalization method. As described earlier, and in detail in Wearden (1992), in temporal generalization, people initially receive examples of a standard duration (e.g. a tone 400 msec long), then are given comparison durations, some longer than the standard, some shorter, and some equal to the standard in duration, and have to judge whether or not each comparison is the standard, using a "Yes/No" response, with feedback being given after each response. The experiments I will describe sometimes deviate slightly from this method, but the deviations are unimportant for our purposes.

Wearden, Wearden, and Rabbitt (1997) used temporal generalization, as well as some other timing tasks, to investigate possible age-related changes in timing behaviour in a sample of community-resident elderly people, aged from 60 to 80 years. The sample had been chosen from a larger subject population so that the usual age-related decline in IQ was avoided: the subjects could be split into two age groups (60-69 and 70-79), with average IQ equated, or three IQ groups (lowest, middle, highest third) with age equated.

The temporal generalization gradients were affected by age, in that the older group produced slightly flatter gradients than the younger group (i.e. made more errors in identifying comparison durations as the standard), but the three IQ groups showed much more marked differences, with the temporal generalization gradients from the lowest-IQ third being much flatter than from the highest-IQ third. The steepness of the generalization gradients can be regarded as an indication of the precision of timing, with steeper gradients indicating more precise timing, so Wearden et al.'s results showed a slight decrease in timing precision with increasing age, and a marked decrease in precision with decreasing IQ.

How can SET explain these results? The obvious step might be to try to explain the results in terms of the speed of the pacemaker of the internal clock, using the common idea that the pacemaker slows down with increasing age (see Vanneste, Pouthas, & Wearden, 2001, for discussion). However, this is not how SET was used to explain the differences, which were attributed to differences in temporal memory variability rather than pacemaker speed.

Wearden (1992) derived a number of quantitative models of temporal generalization performance in humans from earlier ideas by Church and Gibbon (1982). The basic structure of the model supposed (a) that the comparison durations were timed without error, (b) that the memory of the standard duration, which resides in reference memory, is subject to random variability around and accurate mean, and (c) that the decision as to whether or not the comparison is the standard is based on a comparison between a sample from reference memory and the (accurately timed) comparison duration (which resides in the accumulator/working memory).

Data in Wearden et al. (1997) could be accurately simulated using this model by assuming that the memory of the standard (400 ms) duration became more variable (a) with increasing age and (b) with decreasing IQ, with the variability being more sensitive to IQ than age. Thus, the burden of explaining between-group differences falls not on potential differences in how the internal clock works, but on potential differences in reference memory representations. Why is this?

Wearden et al. (1997) followed the route set down by "classical" (i.e. animal-based) SET, where the main source of variability in timing was supposed to reside not in the operation of the clock (although this might make a small contribution to variability), but in storage in reference memory of "standards" or "references" used for the task. Put casually, behaviour on a timing task is variable from one trial to another not because the subject cannot *time* the intervals accurately, but because the subject cannot *remember* the references accurately.

The history and definition of the concept of reference memory in classical SET is discussed in detail in Jones and Wearden (2003, 2004), but one root of the idea that reference memory was the main source of variance in timing comes from considerations of how animals are trained. On an FI schedule, for example, animals do not immediately exhibit accelerating response rates when exposed to the schedule, but need tens or hundreds of reward deliveries before behaviour changes. Suppose that, on FI, the reward occurs *t* seconds after the previous reward. According to classical SET, *t* is in all cases timed accurately (that is, the animal does not underestimate or overestimate the real time of reward), but on each trial, the value of *t* is "misremembered" before being stored in reference memory. On some trials, *t* is remembered as being longer than its real value, and on other trials shorter, but these instances are stored in reference memory, which over a large number of training trials develops to the form of a Gaussian distribution, with mean *t* and some variability. The animal performs by sampling from this memory distribution on each trial (with each sample producing a slightly different value), and uses the sample as an "estimate" of when the reward is due. The estimate varies from trial to trial, and so does the behaviour as a consequence. The variability here arises from *memory* variability and not from *timing* variability.

Droit-Volet, Clément, and Wearden (2001) studied temporal generalization performance in children of 3, 5, and 8 years, with standards of 4 and 8 seconds (children of this age do not spontaneously count), and found that gradients were flattest in the 3 year-olds, less flat in the 8 year-olds, and only slightly less steep than adult gradients at 8 years of age. Like Wearden et al. (1997), they modelled performance by assuming that reference memory variability varied with age, being greatest in the youngest children (see also Droit-Volet, 2002). Their modelling also had other aspects not relevant to this discussion.

In another study, McCormack et al. (1999) examined temporal generalization performance in adults and children. Their data were similar to those obtained by Wearden et al. (1997) and Droit-Volet et al. (2001): the youngest children they tested (5 years old) had more variable temporal generalization gradients, student-age adults showed the most precise timing, and timing variability increased with age. However, their model assumed almost the opposite of that proposed by classical SET: they supposed that the memory of the standard was variance-free, but that the timing of the comparison stimuli was subject to "noise". In effect, they proposed that the reference memory was perfect (at least in adults) but that timing variability resided in the perception of the "raw" durations, presumably resulting from trial to trial variability in the rate of the internal clock. So, for example, if the pacemaker speed varied from one trial to the next more in young children and very old adults than in students, the differences observed in timing behaviour could be explained.

A theoretical problem is that as long as the models contain a scalar (i.e. Weberian) source of variability somewhere in the time-representation system (either in the clock, or the reference memory), then they will fit data equally well. The influence of classical, animal-based, SET biased some recent modelling towards maintaining its view that the principal source of variability in timing comes from reference memory, but as Jones and Wearden (2003, 2004) point out, the conditions of human experiments are very different from studies with animals. Student-age adults can perform well on temporal generalization tasks after receiving just a few presentations of the standard (as few as one, see Jones & Wearden, 2003), so the development of a Gaussian reference memory resulting from the misremembering of many instances of presentations of the standard seems highly implausible.

The idea that the main source of variability in human timing may not reside in reference memory also comes from so-called "episodic" timing tasks, where reference memory seems impossible to use. Wearden and Bray (2001) developed an "episodic" temporal generalization procedure, where the subject received two stimuli (e.g. two tones) separated by a short gap, and had to decide whether or not they had the same duration. The tones were never repeated, and the subjects knew this, but were drawn randomly from different duration ranges, and the two stimuli presented on the trial had one of a series of different duration ratios (i.e. one was 25% the length of the other one, or 50%, or some other value). Wearden and Bray showed that the "proportional" timing superimposition property was found in this condition, even though it seemed highly unlikely that any kind of reference memory was used.

More recently, McCormack et al. (submitted for publication) have used a variant of Wearden and Bray's method to test timing in children, and have found the same pattern of decreasing timing variability with increasing age that is found in "normal" temporal generalization. This suggests that variance due to perceptual (i.e. clock) processes plays an important role in developmental studies as well as, or instead of, the memory variance usually used in modelling.

In general, although the connection between animal Psychology and human time perception has been useful in the development of "human" SET, the concept of reference memory "inherited" from classical SET may not be helpful in understanding all aspects of human timing. Jones and Wearden (2003, 2004) discuss some other difficulties with the classical notion of reference memory when applied to data from humans.

Overall, therefore, although the use of internal-clock-based models derived from SET has been important in understanding developmental issues, some theoretical difficulties have led to a partial reconceptualization of SET itself, both from the point of view of where variability comes from in the system, and how reference memory works. The common-sense view that the operation of the internal clock itself is a principal source of timing variability seems to be gaining strength, as well as the idea that memory processes in humans may not operate in terms of the gradual accumulation of large numbers of instances, but may have other more flexible structures (Jones & Wearden, 2003).

Figure 4 about here

Conclusions: Roots and branches of the tree of time

To provide a brief summary of some of the connections that have been traced in this article, Figure 4 shows some of the roots (i.e. antecedents) and branches (i.e. developments) of the internal clock models of Treisman and SET.

Reading from bottom to top, we begin with 19th. century psychophysics, with its introduction of "laws" like Weber's law. A slightly later landmark is provided by body temperature studies, and psychophysics from the same period. The 1960s saw the emergence of the first fully-fledged internal clock theory with the publication of Treisman (1963), and this was followed 20 years later by the "standard" version of SET, influenced as it was by operant conditioning studies and animal psychopharmacology. SET gave rise to what might be called "human" SET, and this has been followed in the present day by developmental studies and other work (see Wearden, 2003, for discussion).

The present article has shown the vitality of the idea of an "internal clock" as an explanation of some aspects of human timing but has not, for reasons of space discussed alternatives, but Wearden (2001) and Droit-Volet and Wearden (2003) put internal clock models in the context of their competitors. Not everyone accepts that internal clock theory is the only way to understand internal timing mechanisms in animals and humans, although almost everyone would agree that the research internal clock theory has spawned has been valuable.

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Figure legends

Figure 1: Data from Hoagland (1933, 1935). The experimental subject was Hoagland's wife, whose body temperature varied as a result of influenza. The data shown are the time take to count up to 60, at the estimated pace of 1 count per second, as a function of body temperature (degrees Farenheit, following Hoagland's original plot). The line shown is the best-fitting regression line.

Figure 2: Upper panel. Outline of Treisman's 1963 internal clock model. The sketch follows Treisman (1963), Figure 7, p. 19, and only the "verbal selective mechanism" is omitted. Arrows show direction of flow of information in the system. Lower panel: Diagram of scalar expectancy theory, after Gibbon, Church, and Meck (1984). Arrows show direction of flow of information in the system

Figure 3. Upper panel: Data from reproduction experiment of Woodrow (1930), using intervals up to 1.5 second. Standard deviation of reproductions, expressed as a fraction of the to-be-reproduced interval, is plotted against duration value. Lower panel: data from Catania (1970). Pigeons were rewarded for waiting between 1.27 to 24.4 s. Values shown are standard deviations of wait times (expressed as a fraction of the mean wait time/latency), plotted against mean latency.

Figure 4. Summary diagram of principal "roots and branches" of internal clock theory, with approximate dates.

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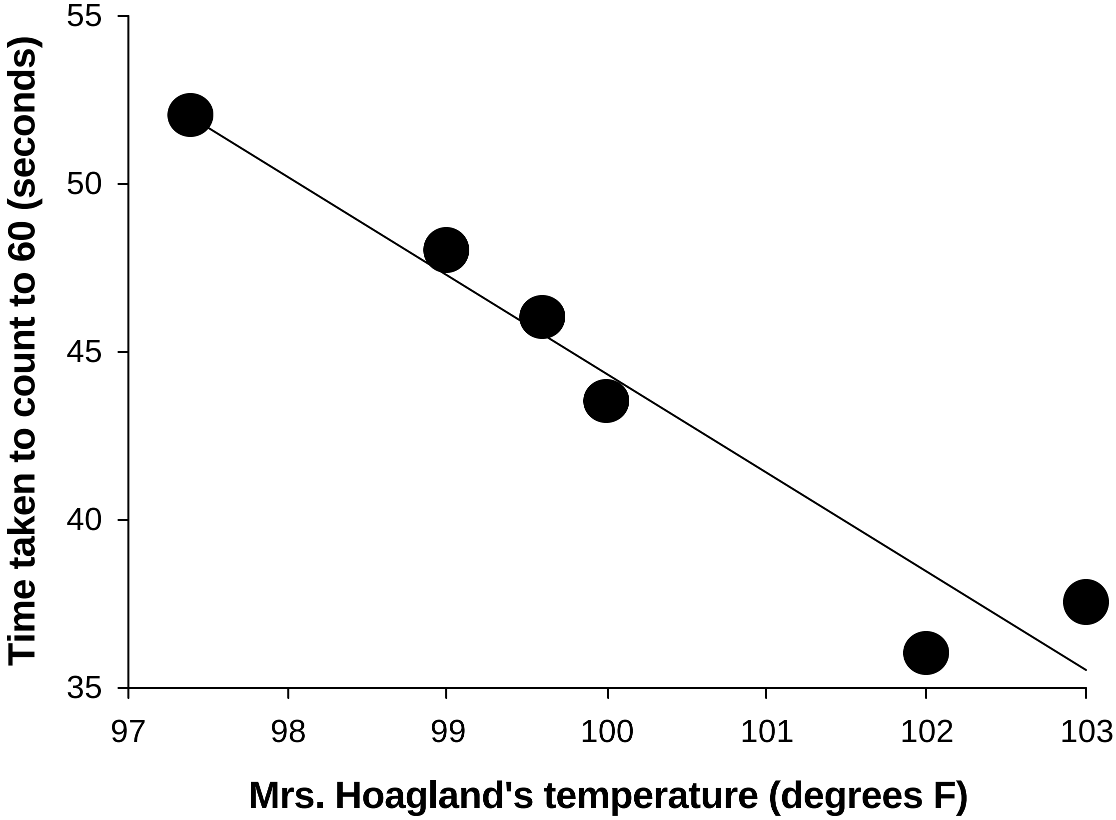
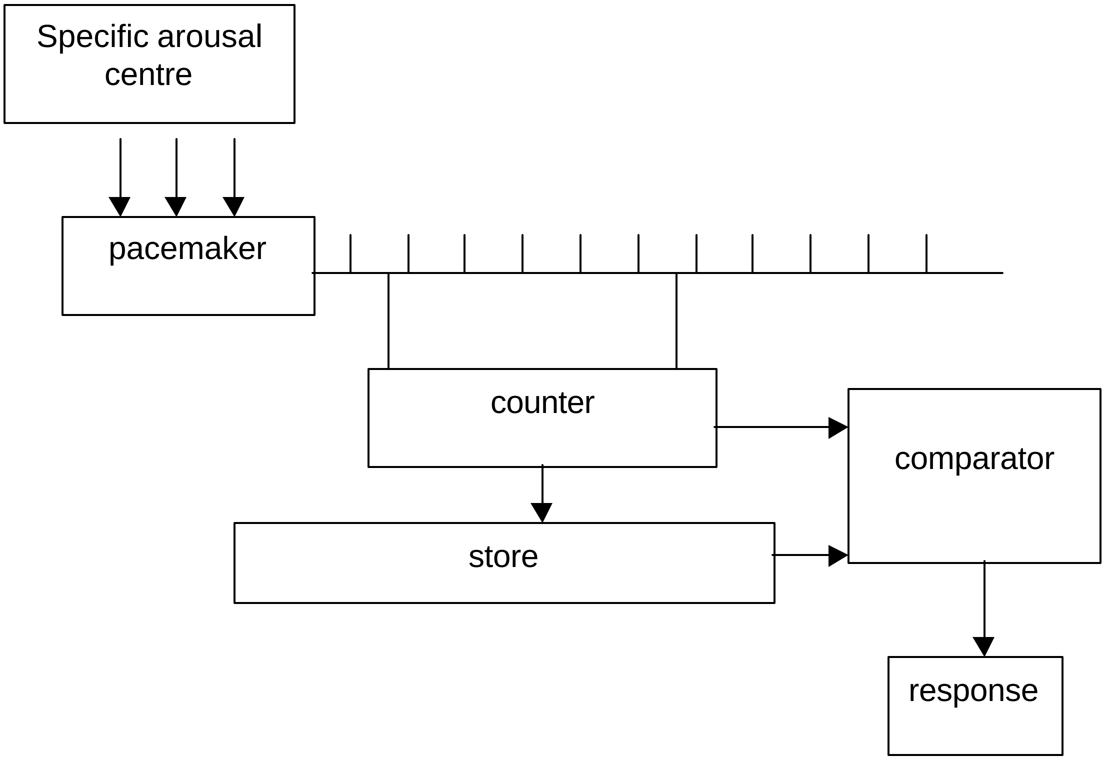
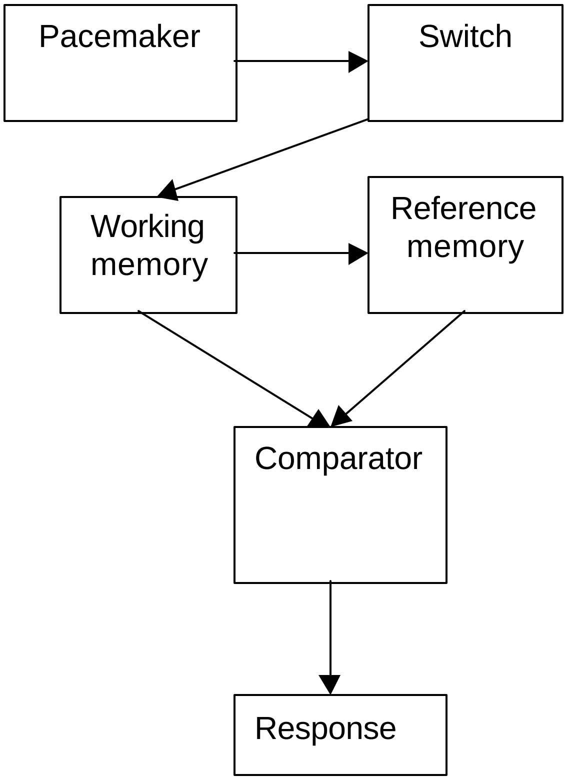
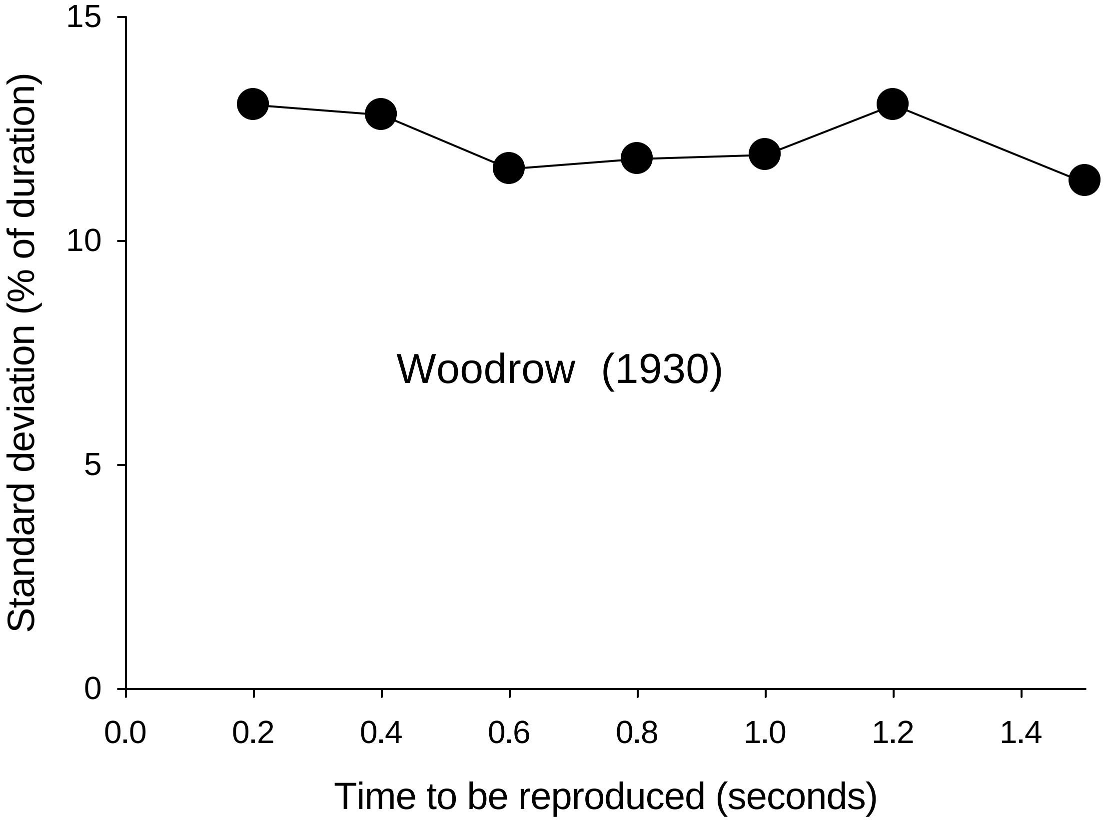

55
50
45
40
35
97
98
99
100
101
102
103
Time taken to count to 60 (seconds)
Mrs. Hoagland's temperature (degrees F)

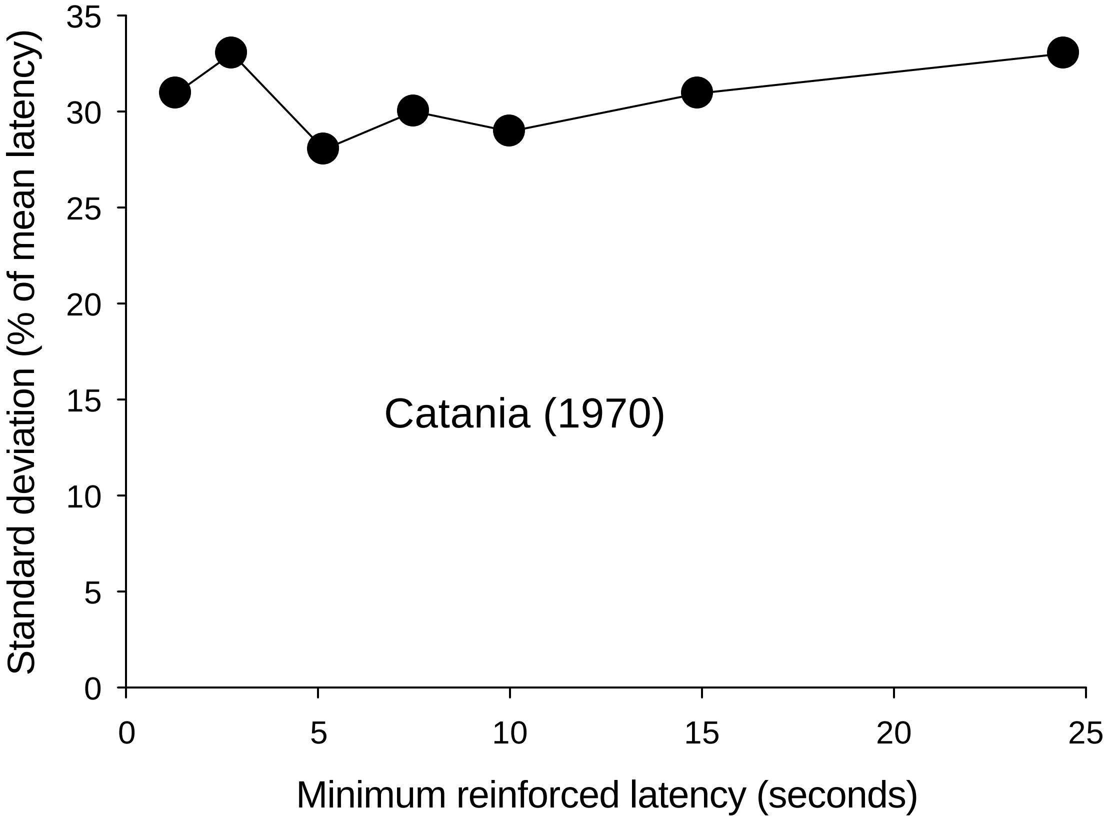
TREISMAN (1963)



GIBBON, CHURCH, and MECK (1984)




Standard deviation (% of duration)
15
10
5
0
Woodrow (1930)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time to be reproduced (seconds)


Standard deviation (% of mean latency)
35
30
25
20
15
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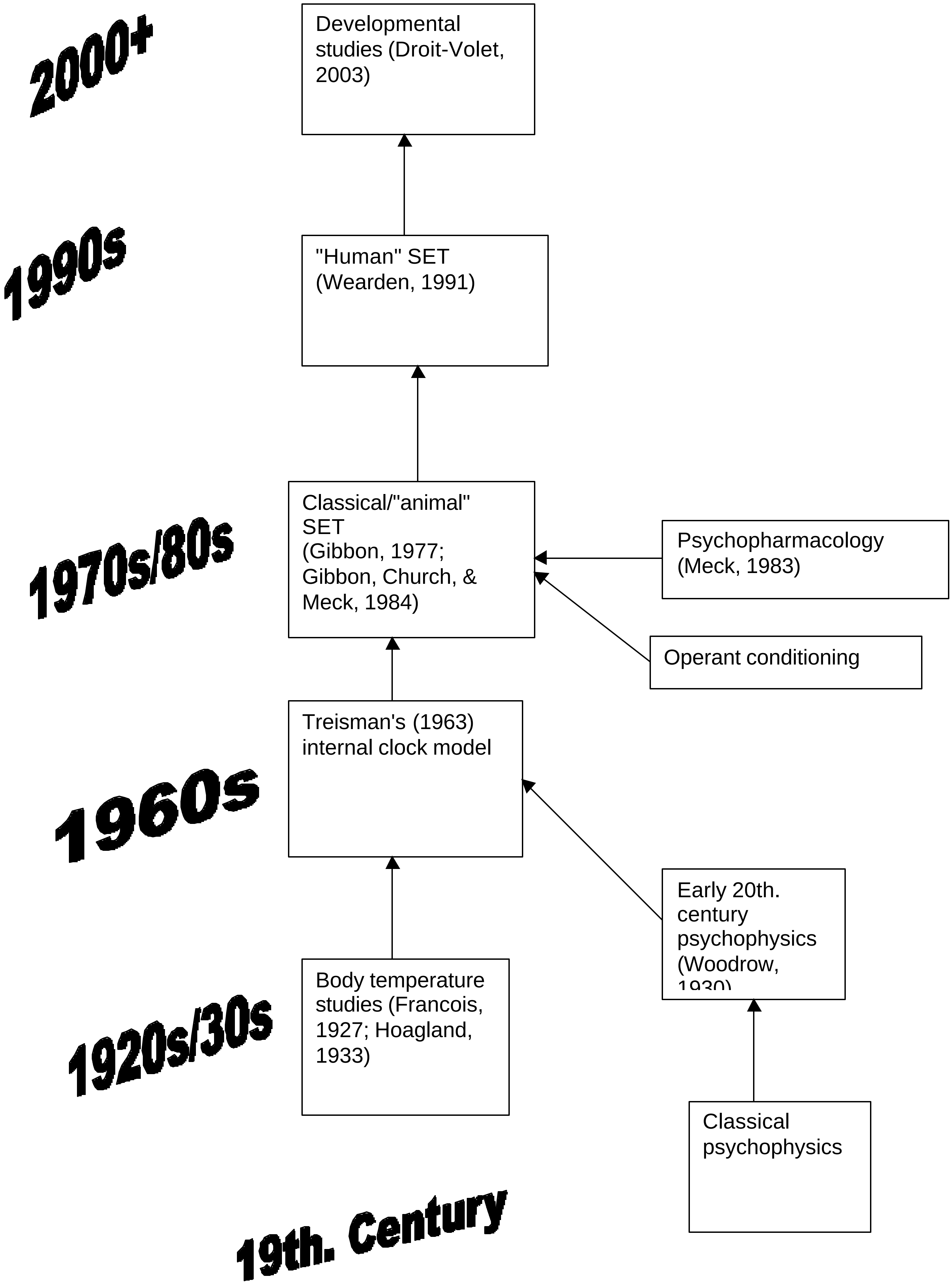
5
0
Catania (1970)
0
5
10
15
20
25
Minimum reinforced latency (seconds)


2000+
Developmental studies (Droit-Volet, 2003)
1990s
"Human" SET (Wearden, 1991)
1970s/80s
Classical/"animal" SET (Gibbon, 1977; Gibbon, Church, & Meck, 1984)
Psychopharmacology (Meck, 1983)
Operant conditioning
1960s
Treisman's (1963) internal clock model
Early 20th. century psychophysics (Woodrow, 1930)
1920s/30s
Body temperature studies (Francois, 1927; Hoagland, 1933)
19th. Century
Classical psychophysics