About the (Non)scalar Property for Time Perception

Simon Grondin

Abstract

Approaching sensation scientifically is relatively straightforward. There are physical attributes for stimulating the central nervous system, and there are specific receptors for each sense for translating the physical signals into codes that brain will recognize. When studying time though, it is far from obvious that there are any specific receptors or specific stimuli. Consequently, it becomes important to determine whether internal time obeys some laws or principles usually reported when other senses are studied. In addition to reviewing some classical methods for studying time perception, the present chapter focusses on one of these laws, Weber law, also referred to as the scalar property in the field of time perception. Therefore, the question addressed here is the following: does variability increase linearly as a function of the magnitude of the duration under investigation? The main empirical facts relative to this question are reviewed, along with a report of the theoretical impact of these facts on the hypotheses about the nature of the internal mechanisms responsible for estimating time.

Keywords

Temporal processing • Scalar timing • Weber law • Internal clock

Experimental psychology is rich of a very long research tradition in the field of sensation and perception, and in the field of animal behaviour. The study of time perception has been part of this tradition. The reader can find in the literature old reports of fine investigations related somehow to psychological time. Amongst others, experimental psychology already offered, towards the end of the nineteenth century, a few systematic investigations by Vierordt [1] and Bolton [2] on rhythm. As well, in his classical book, *The Principles of Psychology*, James [3] already established several distinctions about the experiences of time, including the idea of a "specious" present (a unified moment, distinct from past or future), the transition from simultaneity to successiveness, and the difference between time

S. Grondin (✉)
École de psychologie, Université Laval,
2325 rue des Bibliothèques, Québec, QC,
Canada G1V 0A6,
e-mail: simon.grondin@psy.ulaval.ca

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in retrospect and experiencing the passage of time (referred to as retrospective and prospective timing in the next paragraph). Amongst the classical publications of the twentieth century, the books by Fraisse [4, 5] on rhythm and on psychological time were certainly, at the moment of their publication, significant syntheses of the main pieces of information in the field. Moreover, a meeting on timing and time perception, held in New York in 1983 and leading to the proceedings edited by Gibbon and Allan [6] proved to be a critical event as people from different perspectives on time perception were grouped together. Until then, time perception researchers studying humans and those studying nonhuman animals worked on similar topics, but quite independently. Both posited the use of an internal clock (the pacemaker-counter device described later in this chapter), and emphasized a fundamental characteristic of the clock. For researchers with a background in human psychophysics (usually interested in sensation and perception), the Weber law was a central concern; as well, researchers on animal timing paid special attention on a feature that is essentially equivalent, the so-called scalar property (described below). Since that meeting, many methods used for studying animal timing were used also for studying human time perception, which allowed for additional testing of the scalar property. Because a theory based on this internal clock perspective, and emphasizing this scalar property has been dominating the field of timing and time perception in the last decades, assessing the validity of this scalar property is a fundamental issue, an issue that is at the heart of this chapter.

Experimental and Analytic Tools for Studying Time Perception

Methods

The timing and time perception literature offers a myriad of methods for investigating the nature of psychological time, its functioning and properties [7]. Of critical importance when approaching the time perception literature is to distinguish retrospective and prospective timing (see Fig. 1). In the former case, participants in an experiment have to complete a task or an activity and they receive no prior warning that they will have to estimate the duration of this task or activity subsequently. With retrospective timing, which is associated with memory processes [8, 9], participants will either make a verbal estimate (with chronometric units) of the duration or reproduce the duration. The choice of activity is of course partly linked to the duration of the task, temporal reproduction being difficult to apply when an activity lasts many minutes for instance. The structure of events is critical for remembering duration retrospectively [10]. Note that recent investigations with retrospective judgments cover intervals lasting a few minutes up to almost an hour [11–15]. Finally, retrospective judgments about time could also cover the remembering of the duration of public events [16, 17] or autobiographical events [18, 19] lasting days or months and occurring years ago.

The investigations involving prospective timing, i.e., in conditions where participants are informed before they begin a task or an activity that timing will be required, are much more numerous in the timing literature, involve a large variety of methods (tasks or procedures), and are the focus of the present chapter. In addition to the methods described earlier—verbal estimates and interval reproduction—that can also be used for prospective timing, this paradigm includes the use of interval production where a participant produces an interval, with finger taps for instance, matching the interval reported in temporal units by an experimenter.

A fourth method used in a prospective timing condition could be referred to as interval comparison. There are various ways of comparing the relative durations of several intervals. On the one hand, it is possible to present two successive intervals and to ask whether the second one is shorter or longer than the first one (a forced-choice procedure); and it is also possible to make multiple repetitions of the first and of the second intervals (sequences of empty intervals marked by brief sensory signals) as is the case in experiments where rhythm is under investigation. This is a typical discrimination procedure in psychophysics. On the other hand, a participant

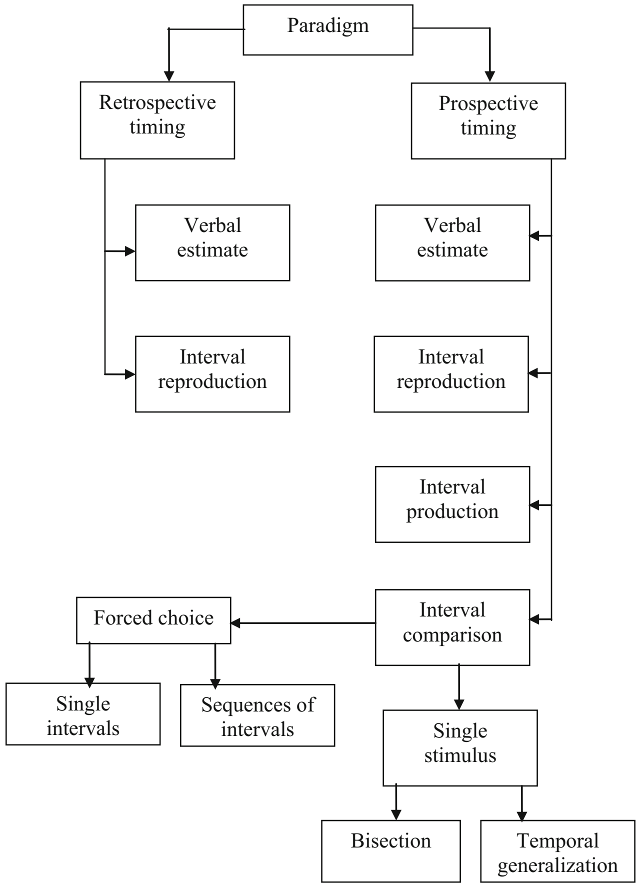

Fig. 1 Schematic view of the main experimental methods for studying time perception (from Grondin [24])

might be asked to judge one of two, or of many intervals, after each presentation of one interval. This general feature was referred to by Allan [20] as the single-stimulus method of presentation, and could also be viewed as a kind of categorization task. There are two classical cases of single-stimulus method in the animal, and now human, timing literature. One is the temporal bisection task where the shortest and the longest of a series of intervals are presented several times at the beginning of the experiment. After these presentations, a participant has to determine, on each trial, if the interval presented is closer to the short or to the long interval previously presented. With a temporal generalization task, the standard interval (at midpoint of a series of intervals) is first presented several times, and then, after each presentation of an interval, a participant should indicate whether the presented interval is similar or not to the standard. Note finally that there are many other methods used in prospective timing (for instance, the peak procedure developed in animal timing, and different adaptive procedures, developed in psychophysics, where the relative length of intervals to be discriminated are adapted from trial to trial).

In the case of the bisection method for instance, a psychometric function could be drawn by plotting the probability of responding "long" on the y axis as a function of the series of intervals (from the shortest to the longest) on the x axis. An index of performance (for instance one standard deviation on the curve[1]) can be

[1] Traditionally in psychophysics, when a psychometric function is used, the distance on the x axis corresponding to 75 and 25 % of "long" responses, divided by 2, is the discrimination threshold.

extracted from the function. This index, divided by the mid-point between the shortest and longest intervals provides an estimate of the Weber fraction for a given experimental condition. In the case where psychometric functions are based on a forced-choice procedure, i.e. when both standard and comparison intervals are presented on each trial the Weber fraction is obtained by dividing the discrimination threshold by the value of the standard interval.

Two Laws and One Theoretical Position

One should expect two fundamental qualities from a timekeeping device. This timing system must be able to remain close to the target duration to be timed, i.e., over a series of trials, the mean estimated intervals (central tendency) must be close to real duration. The deviation from the target duration is called the constant error. As well, the variability (dispersion) of this series of trials must be kept as low as possible by the device [21]. As we will see below, this temporal variability is quite important because it is a critical feature of the most cited model in the field of timing and time perception, the Scalar Expectancy Theory [SET—22, 23]. This variability is often described in terms of Weber fraction, described below.

Laws

Remaining close to real duration could be reformulated in term of the psychophysical law. If remaining close to real duration for one given interval is a critical issue, having a system for which the feature applies over a large range of duration is also critical. In psychophysics, one fundamental issue is the relationship, for a given sensory continuum, between the psychological magnitude and the physical value. For instance, does the psychological magnitude increase exponentially, linearly or logarithmically as with the increase of the physical magnitude? In general, for the different sensory continua, the relationships can take several forms that can be summarized within the so-called power law [25]. Applied to time, the law could be reported as follows:

$$E_T = kT^N \quad (1)$$

where E_T is the estimated time, T the physical time, k a constant related to the intercept. The exponent N, which is generally considered the signature of the sensory continuum under investigation, is close to 1 for time. Indeed, defenders of SET usually report that the exponent value is one [20]. However, there are reasons to believe that the exponent value is often closer to 0.9 (see the extensive review by Eisler [26]).

The psychophysical law is one of two major issues in psychophysics, the other one being related to the variability of the sensory experience: Does variability increase linearly as a function of the magnitude of physical stimuli? According to what is referred to in psychophysics as Weber's law, it does [27].

In its strict form, and in the context of timing, the variability (σ) of time estimates increases linearly with the duration of the interval to be timed (t):

$$\sigma = kt \quad (2)$$

where k is the Weber fraction ($k = \sigma/t$). In other words, the variability to time ratio, sometimes known as the coefficient of variation in the timing literature, should be constant. This relation (Eq. 2) is referred to as Weber's law. There are other forms of Weber's law (for instance, $\sigma^2 = k^2t^2$, Getty [28]; see Killeen and Weiss [29] for a general model of Weber's law for time). The next sections are dedicated to empirical reports where the validity of Weber's law for time is tested, and it is indeed the main focus of the present chapter.

Theory

Over the past 50 years, the field of time perception has been guided by one very important theoretical proposal: There is an internal, single, central clock, and this clock is a pacemaker-counter device [30, 31]. This view can be summarized as follows. The pacemaker emits pulses that are accumulated in a counter, and the number of pulses counted determines the

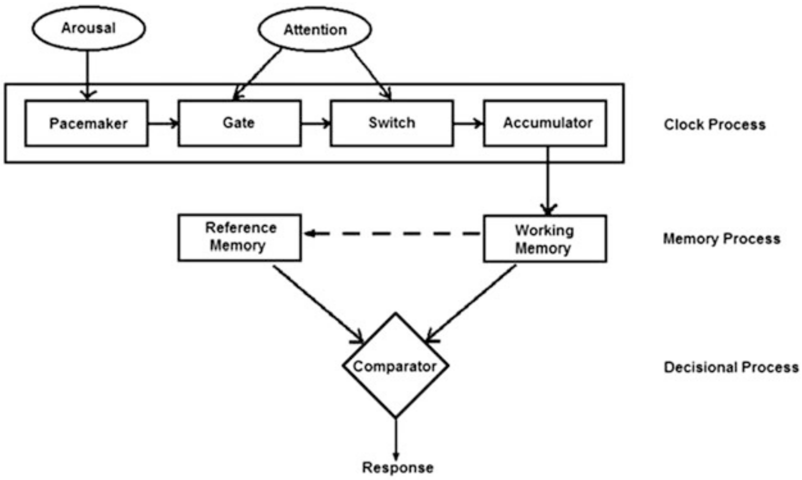

Fig. 2 An illustration of the three levels of processing in a timing task where errors could occur. Note that at the clock level, errors may also depend on arousal, which is influencing the pacemaker's rate, and on attention, which is acting on the amount of pulses passing (gate), and on the moments where the timekeeping activity starts and stops (switch) (adapted from Zakay and Block [8])

perceived length of an interval (the experienced duration). Why would someone make errors in judging time depends on several factors. While older studies have focussed primarily on the properties of the pacemaker [32], there are other sources of variance. Indeed, Allan and Kristofferson [33] pointed out that "…the input process is thought as one which takes a measure of the temporal extent of a stimulus pattern, compares the measure either to an internal standard or to the memory of a measure of a standard stimulus, and triggers a response, which may or may not be biased, depending on the outcome of the comparison process" [33, p. 26]. The reader probably recognizes the three levels of processing—the clock (the input process), memory and decision-making—which have been emphasized since in the information processing version of SET [34]. In other words, nearly 40 years ago, these authors noted how critical these three processing levels are for accounting for timing and time perception (Fig. 2).

SET, which has been a very popular theory of timing over the past 30 years, as noted earlier, is characterized by two basic features [35–37]. First, in terms of the psychophysical law, the relation is supposed to be linear and the exponent equal to 1, a feature that is disputable, as noted earlier. The second feature stipulates that the proportion between variability and mean is *scalar*, i.e., is supposed to be constant; in other words, Weber's fraction, k, is constant. When the psychometric functions obtained with different target durations are plotted on a relative time scale, they should superimpose. In brief, with SET, a time-scale invariance principle should apply. The reader will find in this book many chapters describing timing models where the scalar property is not that central (see also review articles: [24, 38, 39]).

Empirical Facts

This portion of the chapter is dedicated to a brief review of some experiments where the Weber's law for time was tested. When approaching the validity of this law for time, there are at least two key issues that might be considered: what range of durations are we dealing with and does the same conclusion hold when different methods are used for estimating the variability as a function of base duration. In the case of the first question, it would obviously not be reasonable to search for a mechanism that would account for the processing of microseconds or of few milliseconds (as is necessary in echolocation or sound localization) and for hours (like circadian rhythms: see [40–43]). The interest of experimental psychologists for Weber's law for time, or the scalar property of timing, usually covers a few hundreds of milliseconds up to a few seconds, which corresponds to the range within which the processing of speech, motion coordination and the conscious estimation of time occur.

Recent Data: Restricted Range

In a recent article, Merchant et al. [44] completed a systematic investigation of Weber's law for time. What is interesting in this paper is the fact that not only perception and production methods were used, but the modality for marking intervals was manipulated (auditory vs. visual stimuli), as well as the number of intervals presented (single vs. multiple). With the tasks involving only perceptual processes (discrimination), it is known that changing the number of intervals presented for judging time influences the performance levels. Would the Weber fraction remain constant, for any temporal task, for specific conditions where different performance levels are expected?

Although there were quite a bit of differences among the experimental conditions, the results of Merchant et al. [44] showed a strict compliance to the scalar property: the variability increased linearly as a function of interval duration, and this observation applied in all tasks. Although the demonstration was convincing, there is one fundamental piece of information that should be reported here about this study: the standard intervals used in this study varied from 350 to 1,000 ms. Indeed, all intervals presented to the 13 participants of this study were briefer than 1,300 ms. As we will see in the next paragraphs, restricting the investigation to this duration range makes a huge difference when comes the moment to decide whether or not the scalar property holds for time perception.

That said not all reports with intervals briefer than 1 s revealed that the Weber fraction is constant. For instance, in a series of experiments where the single-stimulus (categorization) method was used, this fraction was higher at 1 than at 0.2 s, and this effect was neither due to the number of intervals used to determine threshold, nor to the range of intervals to be compared [45].

In one recent series of experiments designed specifically to test Weber's Law, the question was addressed this way. Let's have a restricted range of durations, between 1 and 2 s, and see if the Weber fraction is constant and if it is constant whatever the method used to determine the performance levels [46]. This could be seen as a kind of extension of the Merchant et al.'s study [44], but involving a new range of durations. Once again, the series of tests involves perception and production tasks, but also single and multiple interval presentations. Once again, even if the estimated variability was expected to differ across methods, the Weber fraction should remain constant. Would this also be true once again for another, admittedly restricted, range of durations, i.e. between 1 and 1.9 s?

In the first experiment of the series reported in Grondin [46], participants were presented with a standard interval 1, 3 or 5 times with a series of 2, 4, or 6 brief auditory signals. After 2,166 ms, a comparison interval was presented 1, 3 or 5 times with a series of 2, 4, or 6 brief auditory signals. The task of the participant was to report whether the second interval(s) was(were) shorter or longer than the first(s) (duration discrimination). There were 4 standard-interval conditions: 1, 1.3, 1.6, and 1.9 s. In the 1-s standard condition, the comparison intervals lasted 860, 900, 940, 980, 1,020, 1,060, 1,100, and 1,140 ms and in the other standard conditions, the comparison intervals were multiplied by 1.3, 1.6 and 1.9. In other words, the comparison intervals ranged, for instance, from 1,634 to 2,166 ms in the 1.9-s standard condition.

Individual psychometric functions were drawn in each experimental condition and a Weber fraction was calculated for each condition. As illustrated in the upper panel of Fig. 3, the Weber fraction is higher in the 1-interval condition than in the two other conditions. This is not surprising given that it is known that performance is better when multiple instead of single intervals are presented (see for instance

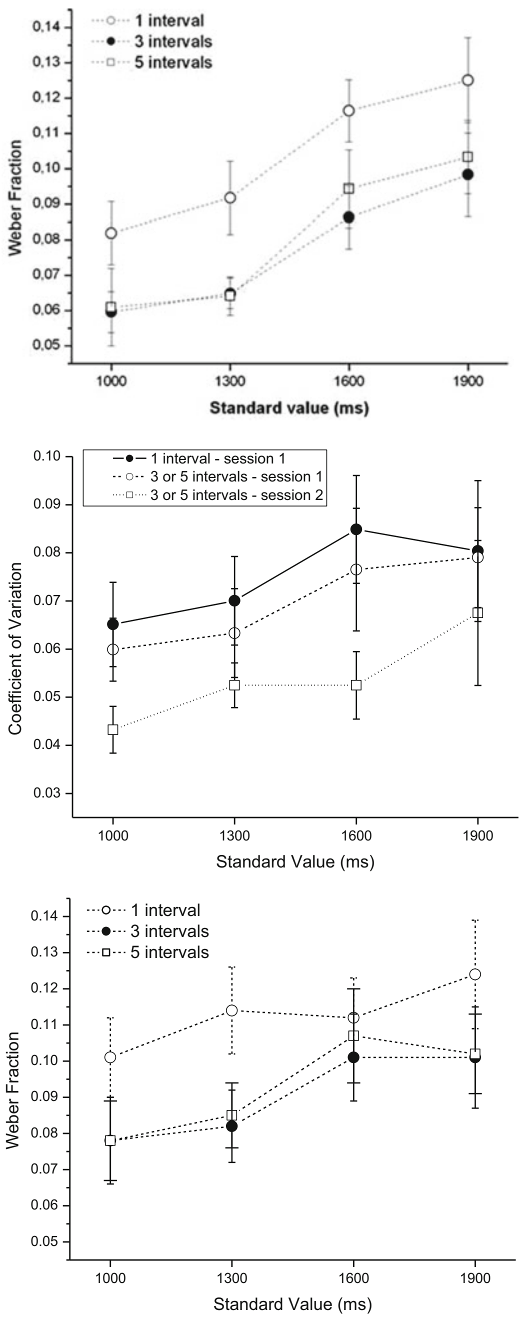

Fig. 3 Weber fractions as a function of time. *Upper panel*: discrimination (Experiment 1); *Middle panel*: reproduction (Experiment 2); *Lower panel*: categorization (Experiment 3) (in Grondin [46])

[47–49]). However, the results also revealed that in the three conditions under investigation, the Weber fraction is not constant. More specifically, the Weber fraction gets higher as the standard interval gets higher. The key finding here is the fact that essentially the same pattern of results was obtained, whatever the level of performance.

The same type of results was reported in Grondin [46] in two other experiments.

In one experiment, participants were presented 1, 3, or 5 intervals marked by 2, 4, or 6 brief sounds. The intervals lasted 1–1.9 s. Participants were asked to reproduce the interval(s) with two brief taps on the keyboard (in Session 2, restricted to the 3- and 5-interval conditions, they also synchronized their taps with sounds). The middle panel of Fig. 3 shows once again that the Weber fraction, which is indeed a coefficient of variation in this experiment (the inter-tap variability divided by the mean reproduction), is not constant. For instance, this coefficient is significantly higher in the 1.9- than in 1.0-s condition.

In the third experiment of this series, the conditions were exactly as in the first experiment. However, instead of presenting a standard and a comparison interval on each trial, the standard was present a few times at the beginning of a block; also, after each presentation of one of the comparison intervals, participants had to categorize the presented interval as shorter, or longer, than the standard. In addition to replicating that performance is improved when more than one interval is presented, the experiment once again showed (see lower panel of Fig. 3) that the Weber fraction gets higher as the standard gets higher.

In brief, whatever the method (discrimination, reproduction or categorization) used in Grondin [46], and whether single or multiple (rhythm) intervals are presented, a violation of Weber's law was observed. The fact that the same principle applies with single and multiple intervals is quite interesting. There are reasons to believe that the functional arrangement of neural systems responsible for timing differs according to whether single or multiple intervals are presented during a timing task [50]. In their attempt to categorize several timing tasks on the basis of the degree of relationships, Merchant and collaborators conducted hierarchical clustering and multidimensional scaling analyses that revealed that single interval mechanisms probably engage neural substrates that are different from the one used when multiple intervals are involved in a timing task. Indeed, there are recent neuroscientific evidences showing that the role of the cerebellum, at least for the processing of subsecond intervals, differs according to the type of temporal processing required, duration-based (single interval presentation) vs. beat-based (multiple interval presentations) processing [51]. These evidences were obtained on the basis of both neurostimulation [52] and functional magnetic resonance imaging [53, 54] investigations.

Bangert et al. [55] also reported recent data suggesting that there is a violation of Weber's law for time. Indeed, they reported that the coefficient of variation is higher at 1,700 ms than at 1,350 ms, where the coefficient is already higher than at 1,175 or 1,000 ms. For brief intervals (270–1,175 ms), there was no such violation of the Weber's law but beyond that point, the Weber fraction increased. In their Experiment 3, which involved intervals ranging from 270 to 1,870 ms, the authors replicated previous findings obtained with a reproduction task, but contrary to what was reported in Grondin [46], there was no violation of the Weber's law for a duration discrimination task. Note however that their Weber fraction was higher (but not significantly different) at 1,700 or 1,870 ms than at 1,350 ms.

Recent Data: Extended Range

When extended to a much larger range of durations, the question of using explicit counting (or some segmentation strategy) or not becomes very critical. Explicit count of numbers reduces very much the Weber fraction from 1 to 2 s, but this fraction remains stable from 2 to 4 s ([56], Experiment 2). Some human data show that the Weber fraction remains constant, even without counting, for intervals up to 24 s for an interval reproduction task [57, 58], and that this fraction is even reduced with longer intervals when explicit counting is adopted [58]. The reduction of the Weber fraction with longer intervals was observed in Grondin and Killeen [57] only with musicians, not with non-musicians, and this observation applies with both the use of explicit counting and singing for segmenting time. Note finally that, when a series of intervals is produced sequentially, the Weber fraction increases with longer intervals (up to 24 s—non-musician participants) in spite of the use of explicit counting [59].

Some other recent data, issued from the animal timing literature, also exhibit a clear violation of the Weber's law when a large range of durations is under investigation [60]. This demonstration was conducted with pigeons with both a categorization and a production method (see Fig. 4).

Revisiting Older Data

The older literature is filled with demonstrations supporting some form of Weber's law, which might be a reason why SET remained so popular over the years. However, a closer look at some portions of what is available in the literature reveals some important signs of the non constancy of Weber's law at some point between 1 and 2 s.

Take for instance the study by Halpern and Darwin [61] on rhythm discrimination. They used a series of clicks marking intervals and reported a linear relationship between the threshold value (one standard deviation on the y axis of the left panel of Fig. 5) and the value of the inter-click intervals (ICI) on the x axis. A close look at the figure indicates that the two data points on the left (lower ICI values) are above the function, which is consistent with the generalized form of Weber's law where it is reported that the Weber fraction tends to get higher with very weak magnitudes of a sensory scale, including time [62]. This could be explained by the part of nontemporal variance in the process (represented

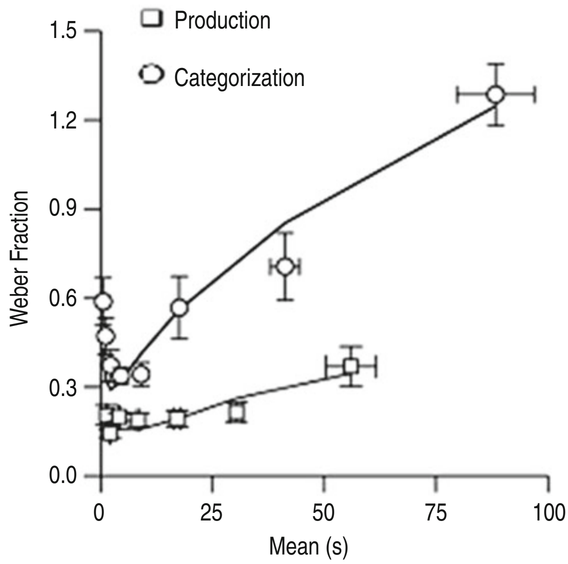

Fig. 4 Weber fraction as a function of the mean in two different temporal tasks, categorization and production, performed by pigeons (in Bizo et al. [60])

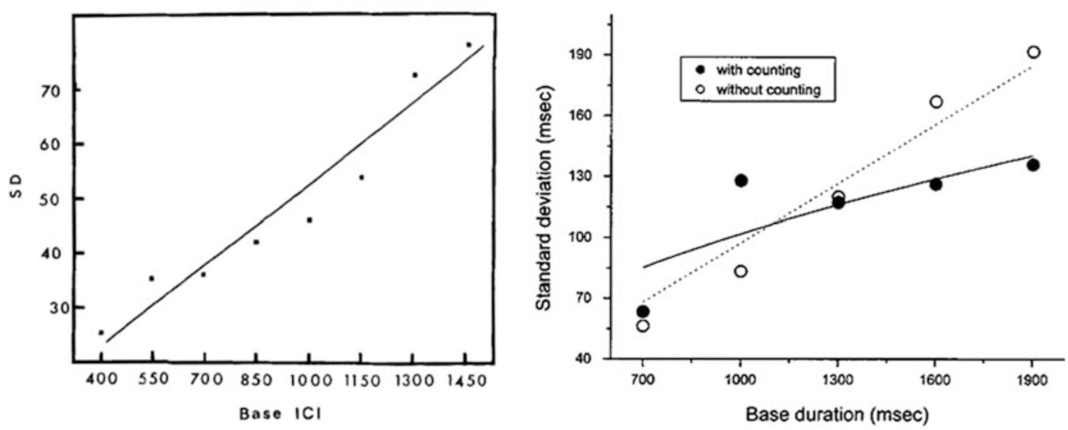

Fig. 5 Growth of the threshold value (one standard deviation on the y axis) as a function of inter-click intervals (in ms) in Halpern and Darwin ([61]—*left panel*) or base duration (standard) in Grondin et al. ([64]—*right panel*) (for specific explanations, see the text)

by *a* in the following description based on Eq. 2: $\sigma = kt + a$). The interesting point here is related to the two points on the right of the function. They are both above the fitted function. Indeed, there is a huge step in the standard deviation value when the base ICI increases from 1,150 to 1,300 ms. What could be argued here as demonstration of the robustness of Weber's law for rhythm discrimination rather contains a tangible sign that there is an important change somewhere around 1.3 s, a sign that there is a deviation from strict proportionality.[2]

[2] The reader will also find a Weber fraction increase for tempo discrimination, from 1 to 1.4 s, in Ehrlé and Samson [63, Table 5].

As well, the results on the right panel of Fig. 5 illustrate a similar phenomenon. In these data reported by Grondin et al. [64] on the duration discrimination of single intervals marked by brief sounds, the threshold value (one standard deviation) increases as a function of time. In this study, it is argued that function is fundamentally changed according to whether a participant is allowed (filled points) or not (empty points) to count explicitly during the task. The function in the no-counting condition (dotted line) accounts reasonably well for the data from 0.7–1.9 s. However, the first three points (lower value on *x*) are below the function and the other two points are above. There is a kind of step between 1.3 and 1.6 s that is negligible in the context of a comparison with a counting condition.

In addition to these two specific cases, the reader may also find several other examples of the violation of Weber's law in the older timing literature. In his review of a few reports on the relationship between the Weber fraction and time, Fraisse [65] reported three clear cases where the Weber fraction is not constant, that of Woodrow [66], Stott [67], and Getty [28]. While the fraction gets higher when the base duration is about 2 s in Stott, it increases after 1.5 s in Woodrow. The data from Getty [28] were collected on two participants, including the author. Their threshold was estimated for the discrimination of single auditory intervals for 15 base durations from 50 to 3,200 ms. The Weber fraction was quite constant from 200 to 2,000 ms, but clearly higher at 2,800 and 3,200 ms.

The reader may also find a composite figure in Grondin [68] where different reports also suggest that, with different methods, there is an increase in the Weber fraction for longer intervals. The data on auditory tempo discrimination from Drake and Botte [47] show a higher Weber fraction with 1.5-s than with 1-s standards. As well, the Weber fraction is higher at 1.2 than at 0.9 s for the discrimination of time intervals presented in sequences marked by visual signals [69]. Moreover, with a task involving the production of a continuous sequence of intervals, Madison [70] showed that the coefficient of variation gets higher when intervals are longer than 1.2 s.

Another composite figure, where the coefficient of variation as a function of time is reported, is proposed in the review paper of Gibbon et al. [71]. In this figure, the results from 28 human and 15 animal studies are reported. The mean features extracted from the general picture by the authors are the following. For very brief intervals (<100 ms), the coefficient of variation is higher as base durations get briefer (which is consistent with a generalized form of Weber's law). Then, from 0.1 to 1.5 s, the coefficient remains constant, and increases again over 1.5 s. Some signs of a new noticeable increase are observable at 500 s.

In brief, there were multiple indications in the old timing literature revealing that the Weber fraction is not constant. Nevertheless, in spite of these indications, many authors assumed that the scalar property holds for time.

Other Challenges: Outstanding Issues

Two main issues could be extracted from this review. First, there is a violation of the scalar property for time perception, and there are multiple reasons to believe that this non constancy of the Weber fraction occurs at some point between 1 and 1.9 s. Secondly, this non constancy is not due to some specific methodological features since the demonstrations were completed with different methods (production vs. perception), in conditions where time intervals are marked with sounds or flashes, and in conditions where either presentations of single or multiple intervals are used. Therefore, the violation of the scalar property seems to be quite a robust phenomenon.

The scalar expectancy theory, described earlier, has been one of the most, if not the most, useful theory of time perception in the past 30 years. One central feature of this theory has actually been its scalar property: the variability to time ratio, or Weber fraction, should be constant over a wide range of durations. Considering the series of evidences provided in the present review, this feature does not hold. Does that mean that SET is obsolete? Probably not, given its power to account for multiple data, either in the human and animal timing literature [72]; however, it is necessary to try to understand the source and meaning of this non-constant Weber fraction.

One or Multiple Timing Devices

A fundamental question that should be asked is whether or not the same timing system is responsible for accounting for temporal judgments whatever the method of investigation employed and whatever the range of durations. If the timing system is a pacemaker-counter embedded within a framework that includes memory and decisional processes, and the predicted output of this entire mechanism is a scalar property, then the "same" (unique, central) perspective is a position difficult to defend. This however does not exclude the possibility that there is a central timing device, as long as the scalar property is not a pre-requisite of the model.

If the question of the central timekeeping device is restricted to a narrower range of durations such as the one used for obtaining the data reported in Fig. 3 (1–1.9 s), and the scalar property is expected from this device, the response is tricky. On the one hand, the Weber fraction is clearly not constant, which should lead to a rejection of the central/unique-device hypothesis. On the other hand, whatever the condition (perception vs. production; single- vs. multiple-interval presentations), the same phenomenon occurs: an increase of the fraction that mostly occurs between 1.3 and 1.6 s. With such a common feature, it remains reasonable to keep believing that the same system is used.

Maybe there is no need to consider if the scalar property holds when time comes to assess whether or not there is a central timekeeping device. And maybe there is no need for positing that there is a central timing device. If there is no unique timekeeping device, we may posit the hypothesis that there is a multiplicity of timekeeping mechanisms, actually because a complete adaptation to real life situations requires a multiplicity of temporal adjustments. Such an avenue though is a difficult one in science. We may also try to remain reasonable and propose the existence of two distinct timekeeping mechanisms, at least, for durations ranging from 100 ms up to a few seconds, i.e. for a range that would cover the processing of speech or motion coordination, as noted earlier.

Two Timekeeping Systems?

Let's return to the right panel of Fig. 5. This figure is essentially saying that there is a point, circa 1.2 or 1.3 s, beyond which there are benefits to be expected from the adoption of a different way of approaching a timing task [56, 58, 64, 73]. Beyond this point, the constancy of the Weber fraction is on shaky ground; but there is actually an option, at least for human observers. It is possible to count explicitly. One can choose to count numbers explicitly, and count rapidly or slowly, depending on the intervals to deal with. If not numbers, one may adopt other strategies including foot tapping like a drummer, imagining the hand of a clock for counting seconds, or even simply singing [57, 59].

Counting explicitly and not counting could be viewed like two different timekeeping systems. However, counting is nothing more than segmenting a long interval into a series of subintervals [29, 74]. The estimation of the duration of each subinterval may require the contribution of the same timekeeping system as the one used for the entire long interval. The idea is to minimize variance. If the summation of the variance of each subinterval, plus the variance associated with the count of the number of subintervals is lower than the variance associated with the timekeeping of the entire interval, then it is advantageous to count.

That said, having two different functions in Fig. 5 (right panel) could be interpreted as the presence of two mechanisms. Tentatively, the crossing point could be viewed like a critical phase change, i.e., a point where the system is transported in a new state or at least, where it is advantageous to adopt a new state. As noted above, this point occurs circa 1.2 or 1.3 s, and 1.3 s is actually a critical duration where the nonconstancy becomes noticeable in numerous timing tasks (Fig. 3). Interestingly, animal timing data also show that intervals in that duration range are critical. In their review of animal and human timing literatures, Gibbon et al. [71] pointed toward a 1.5-s critical value. Even more intriguing is the fact that, in the animal timing literature, 1.2 s is sometimes identified as one of the local maxima, on the time continuum, for sensitivity to time [75, 76]; beyond this value, there is a loss of sensitivity. Therefore, the increased Weber fraction between 1 and 2 s very likely reflects a fundamental limitation for processing temporal information.

The idea of chunking pieces of information for increasing the capability of the information processing system is not new [77, 78]. It is indeed one of the most important features of the human processing system. The same principle is applied here for increasing the efficiency to process temporal information. When intervals reach a point where the processing system begins to be less efficient, the other mechanism—call it chunking/segmenting/counting—is available for dealing more efficiently with the task. If one wants to venture an interpretation in terms of traditional information processing wording, it looks as if the space occupied by long intervals exceeds the temporal capacity of working memory [79–81].

As noted by Grondin [46], the concept of a limited temporal span may remind of the idea that was referred to by Michon [82] as *psychological present* (or *specious* present [3]; or *subjective* present [83]). This concept indeed describes a time window within which it is possible to form a coherent package of information. The point where the Weber fraction increase occurs, somewhere between 1 and 1.9 s, could be interpreted as a way for quantifying the temporal span of this window.

Resolving problems with a two-way approach is far from original in psychology. For instance, in the auditory system, there are two theories—temporal coding vs. place coding—to account for the capability to distinguish sound frequencies. And instead of rejecting one theory or another, it was proved convenient to associate the temporal coding avenue (and volley principle) with the processing of low-frequency components, and the place coding interpretation (including von Bekesy's classical traveling wave theory) with the high-frequency components of sounds. Along that line, there could be an interpretation of temporal information processing in terms of brief vs. long intervals, say, below or beyond 1.3 s, with both systems being always available but the level of sensitivity/efficiency being optimal only for a given duration range.

The reader will find traces of a dual-system approach in the timing literature. For instance, Grondin and Rousseau [84] adopted such an approach for explaining why brief empty time intervals marked by two signals delivered from the same modality are much easier to discriminate than intervals marked by intermodal signals (specific vs. aspecific processors). In their *dynamic attending* theory of time perception, Jones and Boltz [85] distinguished two modes for processing temporal information, a *future-oriented* mode, based on the regularities of events occurring in the environment, and an *analytic-oriented* mode.

Indeed, it would be difficult to specify the exact nature of the mechanism dedicated to the processing of brief intervals. It could be a mechanism dependent on the nature of the signals available in the environment or marking intervals, as noted in the past paragraph, or it could be a *state-dependent network*. According to Buonomano [40, 86] timing does not depend on a clock, but on time-dependent changes in the state of neural networks. In this model, being able to judge duration means to recognize spatial patterns of activity.

Note that other dichotomies are proposed in the time perception literature. As for the duration range, there are indications of sensory-based processing, by opposition to cognitively-based processing, when the discriminations of intervals around 50 ms vs. 1 s are compared [87, 88]. Other authors proposed to distinguish explicit timing, as in repetitive tapping like the one used in consecutive interval productions, and implicit timing like the one used in drawing movements [89, 90].

Conclusion

This review of the literature on the scalar property for timing and time perception reveals that there is actually no such scalar property. The literature is filled with demonstrations that Weber's law does not hold or at least, when it holds, it is for a much restricted range of durations, as in Merchant et al. [44], or when a general picture is taken and explicit counting not forbidden, as in Grondin [62] for instance. The violation of the scalar property for time calls for a re-examination of models, such as SET, based on a clock-counter device. The literature offers multiple alternatives, including the possibility to have multiple timers, to process temporal information on the basis of a frontal-striatal circuitry ([91]; see the chapter by Meck and co-workers in this volume) or, as noted earlier, to read time on the basis of the output of a state-dependent network (see the chapter by Buonomano in this volume).

On the other hand, there is a convergence of findings showing that sensitivity to time is significantly lost when intervals become too long (say > 1.3 s); moreover, we know that humans actually have a trick, explicit counting, for compensating this loss. This may indicate the presence of two fundamental ways of processing temporal information. Cognitive psychology is actually filled with numerous dual-process interpretations [92]. These interpretations, or theories, take several forms like a dichotomy between heuristic/holistic and systematic/analytic systems, associative vs. rule-based systems, or implicit vs. explicit systems, to name only a few. And on some occasions, these distinctions are associated with some specific way with which each cerebral hemisphere processes information. Apparently, it could be proved useful to undertake the neurophysiological study of temporal processing with such a dual-process approach in mind, a dual-process that is provoked by the fact that we have to deal with different duration ranges. Indeed, as stated by Rammsayer and Troche (this volume), one avenue is to posit that there are two functionally related timing mechanisms underlying interval timing. According to these authors, these mechanisms are associated either with the processing of sub-second intervals or with the processing of supra-second intervals.

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