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Changing Sensitivity to Duration in Human Scalar Timing: An Experiment, a Review, and Some Possible Explanations

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Evidence from a number of studies of human timing, using temporal generalization and bisection tasks, suggests more sensitive behavioural adjustment to presented durations under conditions in which the timing task demands discriminations between more closely spaced stimuli. An experiment using temporal generalization demonstrated this effect, as discrimination between a 600-msec standard duration and non-standard stimuli both shorter and longer than 600 msec was better when non-standard stimuli were more closely spaced around 600 msec. A review showed similar effects in other temporal generalization tasks and in a number of bisection studies, where time discrimination improved as the ratio of the long and short standards on the bisection task decreased. A standard model of human temporal generalization explained the experimental data in terms of a decrease in the response threshold under more difficult conditions, rather than changes in the representation of the standard duration. On the other hand, data from bisection could be modelled by assuming the contrary; that representations of the short and long standards of the task were more precise under the more difficult conditions. Explanations of some of these effects in terms of attention to duration and/or arousal-induced changes in the speed of an internal clock were discussed.

The theory of *scalar timing*, originally proposed by Gibbon (1977) and developed later with other colleagues (Gibbon, Church, & Meck, 1984) must surely rank as one of the most successful recent imports from the animal to the human psychological laboratories.

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The theory was originally developed to account for previously collected data from animal timing tasks using temporally constrained reinforcement schedules (Gibbon, 1991), as well as data from tasks later specifically designed to study animal timing, such as bisection (Church & DeLuty, 1977) and temporal generalization (Church & Gibbon, 1982). A complete discussion of this model's application to animal timing is beyond the scope of this article, but Wearden (1994) provides a non-technical introduction, and two examples of recent articles using scalar timing to treat data from animals are Church, Meck, and Gibbon (1994) and Leak and Gibbon (1995).

The first clear demonstration that human timing could conform to the principles of scalar timing was probably that of Wearden and McShane (1988), although the possibility of scalar timing in humans had been discussed previously by Getty (1975) and Zeiler, Scott, and Hoyert (1987). In Wearden and McShane's (1988) study humans repeatedly produced durations between 0.5 and 1.3 sec by responding on two buttons. Short durations were employed to ensure that subjects would not regulate their behaviour by using chronometric counting, and accurate feedback (the time actually produced, accurate to two decimal places in seconds) was given after each production.

Scalar timing theory (Gibbon, 1977; Gibbon et al., 1984) proposes that subjective time produced by the underlying timing mechanism exhibits two properties. The first of these is *mean accuracy*, the requirement that mean estimates of some real time, *t*, should equal *t*. The second requirement is the *scalar property* itself, the requirement that standard deviations of time estimates grow as a constant fraction of the mean. This second property is sometimes tested by constructing a *coefficient of variation* statistic (standard deviation/mean); thus the scalar property requires that this coefficient of variation remain constant as the duration timed changes.

Wearden and McShane's data conformed almost perfectly to both requirements of scalar timing theory. First, the mean time produced coincided almost exactly with the time required. Second, the coefficient of variation of times produced remained almost perfectly constant as the time produced changed (see also Wearden, 1991a), thus clearly demonstrating the scalar property. The coefficient of variation used in studies of scalar timing is a type of *Weber fraction*, and the constancy of this measure with changes in the time requirement imposed is a form of conformity to *Weber's law*.

The absolute size of the coefficient of variation is usually considered a measure of the sensitivity of timed behaviour, in the sense that it represents how closely observations are spaced around the mean, where smaller coefficient of variation values represent more sensitive timing. For example, different animal species were found to differ systematically in the coefficients of variation obtained from measures of their performance on fixed-interval schedules by Lejeune and Wearden (1991), with "higher" animals like cats and rats exhibiting more sensitive timing than "lower" ones like fish and turtles. Wearden (1991a) likewise showed that the timing sensitivity of durations produced by humans in interval production experiments was greater than that of pigeons performing analogous tasks. The question of the way in which the scalar timing system might produce changes in behavioural sensitivity is discussed in greater detail in the General Discussion.

A related way of examining conformity to Weber's law in data is to examine *superimposition* (called *superposition* in the American literature)—the requirement that measures of behaviour superimpose when plotted on the same relative scale. For example, in temporal generalization (Church & Gibbon, 1982; Wearden, 1992) animal and human subjects are required to identify a stimulus of some standard value when this is presented along with durations both longer and shorter than the standard. A temporal generalization gradient can then be constructed in terms of the proportion of identifications of a stimulus as the standard plotted against stimulus duration. Such gradients peak at the standard value (Church & Gibbon, 1982; Wearden, 1992), and fewer and fewer responses occur as the stimulus value becomes more remote from the standard, both above and below. In different experiments, the absolute value of the standard can be varied, and if the stimulus durations presented are expressed as a proportion of the standard value in force, temporal generalization gradients superimpose well—that is, the gradients coincide nearly exactly with one another when they are plotted on the same relative scale. Superimposition has been found to hold in a number of data sets from both animals (Church & Gibbon, 1982) and humans (e.g. Wearden, 1992, 1995) and is regarded as a strong test of Weber's law.

The fact that measures of behaviour from judgements of absolutely different durations often superimpose when plotted on the same relative scale (as proportions of the standard in the temporal generalization case, for example) conveys something of the meaning of *scalar* timing. As the absolute values of durations timed vary, the underlying time scale simply readjusts proportionally, so mean time estimates track time requirements accurately, and as standard deviations vary with the mean, the dispersion of time estimates around the mean always remains relatively the same.

Since 1988, there have been numerous studies of human timing inspired by scalar timing theory (e.g. see Allan & Gibbon, 1991, and Penney, Meck, Allan, & Gibbon, in press, from Gibbon's laboratory; and Wearden, 1991a, 1991b, 1992, 1993, 1995; Wearden & Ferrara, 1995, 1996, from our own). Articles on scalar timing in humans have generally focused on two separate but related issues. One of these has been the mathematical conformity of behaviour to requirements of scalar timing—for example, the question of whether behaviour on timing tasks obeys principles like Weber's law, discussed earlier. The second issue is the use of the theoretical mechanics of scalar timing theory to account for behaviour. Scalar timing proposes that timed behaviour is regulated by a complex underlying mechanism, discussed in more detail later, involving an internal clock consisting of a pacemaker and accumulator with a switch connecting them, as well as memory and decision mechanisms. Some recent studies have used procedures designed to alter one or other part of the proposed mechanism, as, for example, in the recent "speeding up the internal clock" study of Penton-Voak, Edwards, Percival, and Wearden (1996).

In general, the use of the principles of scalar timing to account for some aspects of human timing behaviour has been highly successful, and data from humans frequently conform to scalar timing requirements like superimposition with an almost supernatural precision (see Wearden, 1995, and Wearden & Ferrara, 1996, for some examples). The present article, however, discusses some situations in which the degree of superimposition may vary with experimental conditions. In general, these conditions are those in which the difficulty of the discrimination between the stimuli presented in the timing task is varied. For example, if stimuli have similar durations, discriminating them might be supposed to be more difficult than in the case in which the different stimuli have much less similar lengths.

The present article discusses possible effects of discrimination difficulty on timing sensitivity in three related sections, which follow. The first presents an experiment, using temporal generalization in which discrimination difficulty appears to change timing sensitivity. The discussion section of this experiment is then expanded into a review of other studies that have found similar effects, both from temporal generalization and bisection tasks. The final part of the article addresses possible theoretical treatments of these effects.

The experiment used a temporal generalization technique. The method used very closely follows the procedure developed for human subjects by Wearden (1992) from the original animal experiment by Church and Gibbon (1982) and, like Wearden's original analogue, uses short-duration stimuli to prevent chronometric counting. Four different groups of student subjects were initially exposed to a 600-msec tone, identified as a "standard duration". They then received sets of stimuli, including the standard as well as longer and shorter stimuli, and had to decide whether or not each presented stimulus was the standard. The groups differed only in the values of non-standard stimuli. For two groups, non-standard stimuli were spaced linearly around the standard but differed in the size of the linear steps. For one group (lin150), the step size was 150 msec (thus the stimuli were 150, 300, 450, 600, 750, 900, 1,050 msec); in the other group (lin75), the stimuli were spaced in 75-msec steps around 600 msec. Two other groups also received the 600-msec standard, but non-standard stimuli were logarithmically spaced around the standard. For the different groups, the closeness of the logarithmic spacing was varied, being widely spaced in one group (logA) and more closely spaced in another (logB).

Overall, the different experimental conditions permitted observation of any effects of linear or logarithmic spacing of stimuli around the standard but, more pertinently for the present article, the linear and logarithmic spacing conditions also involved comparison of close and more distantly spaced non-standard durations. Presumably, when non-standard stimuli are closer to the standard, discriminating them from the standard is more difficult than when they are more widely spaced, so any effect on temporal sensitivity (assessed from the generalization gradients in the different conditions) will be evident.

Method

Subjects

Eighty University of Liège undergraduates were allocated to four equal-sized groups.

Apparatus

A Copam 88C computer (IBM-compatible) controlled all experimental events. A standard black-and-white monitor presented experimental displays, and a keyboard registered responses. The stimuli used were 500-Hz tones produced by the computer's speaker. The experiment was controlled by programs written in Turbo Pascal, and timing routines derived from assembly-language programs timed stimuli to an accuracy of at least 1 msec.

Procedure

Subjects were tested individually in a cubicle isolated from external light and noise. All instructions and screen displays were given in French to the French-speaking subjects, but they are presented here in English. For example, subjects' keyboard responses actually consisted of presses on the keys "O" ("*oui*") and "N" ("*non*"), but are described here as "Y" and "N". The conditions for all subject groups were identical except for the values of non-standard stimuli. For the different groups, the stimulus values (in msec, and with the standard duration in italic) were:

lin150: 150, 300, 450, *600*, 750, 900, 1050
lin75: 375, 450, 525, *600*, 675, 750, 825
logA: 301, 378, 476, *600*, 755, 951, 1198
logB: 425, 476, 535, *600*, 673, 755, 847

Subjects were initially given general instructions to attend to the duration of the tones presented first, then to compare the length of each subsequent stimulus with the tone. If they judged that a particular stimulus was the same as the standard, they were to press "Y", and if they judged it was not, they were to press "N". The experiment started with 5 presentations of the standard duration, with presentations being spaced by a random time drawn from a uniform distribution running from 2,000 to 3,000 msec, accompanied by the instruction "Listen to the standard tone". All subsequent stimuli followed a subject's spacebar press (produced in response to a "Press spacebar for next trial" prompt) after a random delay ranging from 1,000 to 3,000 msec. When the stimulus had been presented, subjects were asked "Was that the standard tone? Press Y (YES) or N (NO) keys". The response was followed in all cases by accurate feedback presented on the computer screen (e.g. "Correct. That was the standard", "Incorrect. That was not the standard", and so on), then the presentation of the "Press spacebar for next trial" prompt. The stimuli in each condition (the standard and the 6 non-standard stimuli, see earlier) were arranged into a 7-stimulus series, and 15 series were presented, with the stimulus order in each series varying randomly. Note that unlike some other temporal generalization experiments with human subjects (e.g. Wearden, 1992), the standard was not presented more frequently than any other non-standard stimulus. The experimental session lasted about 15 minutes.

Results

Figure 1 shows the temporal generalization gradients (proportion of YES responses plotted against stimulus duration) obtained from the four different experimental groups. The upper panel shows data from the lin150 and lin75 groups, the lower panel data from the logA and logB groups; thus within each panel the effect of spacing of non-standard stimuli around the standard can be observed. As there is some question (Mackintosh, 1974, p. 491) as to how generalization gradients are best plotted, we also calculated the same data but this time plotted in *relative* terms, where the proportion of YES responses at each non-standard value was divided by the proportion of YES responses at the standard, for the particular condition analysed. This method essentially takes into account different overall levels of responding YES at the standard value in the groups compared.

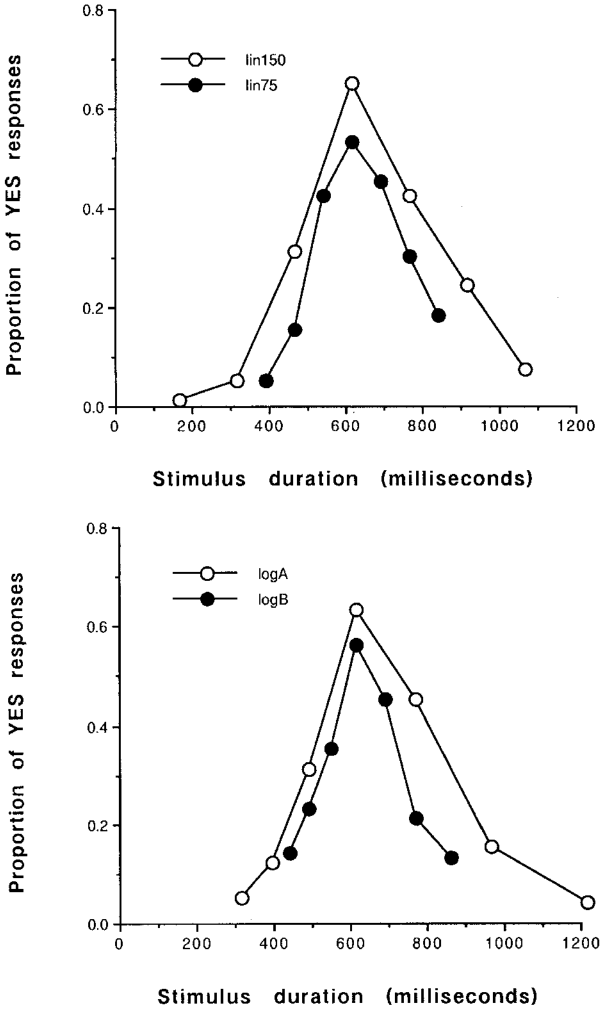

FIG. 1. Temporal generalization gradients (proportion of YES responses, identifications of a presented stimulus as the standard 600-msec duration, plotted against stimulus duration). Upper panel: gradients from the linear spacing conditions (lin150, open circles; lin75, filled circles). Lower panel: gradients from the logarithmic spacing conditions (logA, open circles; logB, filled circles).

Figure 1 shows the absolute proportions of YES responses plotted against stimulus duration. The data when plotted in relative terms were very similar, but these are not shown separately, to save space.

The first point obvious on inspection of Figure 1 was that the temporal generalization gradients were in most cases clearly asymmetrical, with stimulus durations longer than the standard producing more YES responses (i.e. more errors) than stimuli shorter by the same number of linear or logarithmic steps. Thus, for example, more YES responses occurred after 750- and 900-msec durations than after 450- and 300-msec durations in group lin150. When "concentric pairs" (i.e. stimuli the same number of steps above and below the standard) were compared by Wilcoxon tests, many concentric pairs, particularly from the linear conditions, showed significantly more YES responses to the stimulus longer than the standard than the one equally shorter. In group lin150, for example, there were significantly more YES responses to the 900-msec duration than to the 300-msec one, $p = .006$, and in the lin75 group only the closest concentric pair did *not* produce a significant effect of this sort, $p = .03$ and .01 for the others. On the other hand, the only significant concentric pair from the logarithmic spacing groups was the 755/476-msec pair from group logA. Overall, therefore, the tendency for generalization gradient asymmetry was reduced when the stimuli were logarithmically spaced around the standard compared with linear spacing.

Another effect that was apparent on inspection was that the generalization gradient appeared steeper (indicating finer temporal discrimination) when stimuli were spaced more closely around the standard (e.g. groups lin75 and logB) compared with a wider spacing (groups lin150 and logA). This effect was smaller when the gradients were plotted in relative terms rather than absolute terms (as in Figure 1) but was nonetheless still evident. Mann-Whitney U-tests on the proportion of YES responses to stimuli present in both the relevant comparison groups generally supported the claim that gradients were steeper with closer stimulus spacing. For example, in the lin150 and lin75 groups both the 450-msec and 750-msec stimuli are in common, and significantly fewer YES responses occurred to both stimuli in the lin75 group when absolute values were used, $p = .0005$ and .05, respectively, whereas when relative gradients were used, only the 450-msec comparison reached significance, $p = .01$. The logarithmic groups likewise had two durations (476 and 755 msec) in common, and although there was no significant difference in the proportion of YES responses at 476, there were fewer in group logB at 755 msec, with both absolute and relative values, both $p = .001$.

Discussion

Data from the present temporal generalization study resembled those from previous studies with humans (Wearden, 1991a, 1992) in a number of ways. First, data were orderly, with the peak of YES responses occurring at the standard stimulus in all groups. Second, the proportion of YES responses declined systematically with absolute duration difference from the standard, and temporally remote stimuli produced hardly any YES responses, indicating that subjects were attending to the task and that their responses were probably controlled exclusively by stimulus duration. Third, generalization gradients tended to be asymmetrical, with stimuli longer than the standard being more confused with it than stimuli shorter by the same amount, and the asymmetry was reduced when logarithmic, as opposed to linear, stimulus spacing was used. The final result was that the temporal generalization gradient was steeper, indicative of higher sensitivity to duration, when the stimuli were spaced more closely around the standard (groups lin75 and logB) than further away (lin150 and logA). If we assume that the spacing of stimuli around the standard affects the difficulty of discrimination between a just-presented stimulus and the standard, then these results show that this discrimination difficulty apparently modifies temporal sensitivity, with more sensitive timing occurring under more difficult conditions. Theoretical treatments of these effects are discussed later.

Although the data from the study above closely replicated those from other studies of temporal generalization in humans (Wearden, 1991a, 1992; Wearden & Towse, 1994; Wearden, Wearden, & Rabbitt, in press b), one procedural difference from other work was that the standard duration was not presented more frequently than non-standard stimuli, whereas in other work it was. This may have contributed to the fact that the number of YES responses overall, and particularly at the standard, was lower in this experiment than in some others. For example, in almost all the conditions from Wearden (1991a, 1992) and Wearden and Towse (1994), the proportion of YES responses at the standard duration exceeded 0.8, whereas none of the groups in the present study even reached a value of 0.65.

The next section of the article reviews previously collected data, from both temporal generalization and bisection studies, with a view to determining whether discrimination difficulty appeared to have any effect on timing sensitivity in other studies.

Task Difficulty and Timing Sensitivity

In previous work on temporal generalization in humans, the clearest data suggesting an effect of task difficulty on timing sensitivity come from Experiment 3 of Wearden and Towse (1994). This study employed an "episodic" temporal generalization procedure, where two stimuli were presented on each trial. The first was a tone selected randomly from a uniform distribution running from 400 to 600 msec, and the second tone (which occurred 1, 2, 5, or 10 sec after offset of the first) was composed by adding or subtracting various quantities from the first. In one group (GR100), the durations added or subtracted were in 100-msec steps (– 300 to +300 msec), whereas in another group (GR50) they were in 50 msec steps (– 150 to +150 msec). Subjects were asked whether the two durations were the same, and plots of the proportion of YES responses against stimulus difference (Figure 4, p. 259) produced, for all inter-stimulus intervals, plots closely resembling those in the present Figure 1—that is, gradients from GR50 were steeper than, and lay inside, those from GR100. Once again, therefore, if we assume that the task was more difficult when the duration differences were arranged in 50-msec steps, temporal discrimination was better in these conditions.

Many other data sets come from temporal generalization experiments with humans, which used linear spacing of non-standard durations around the standard in 100-msec steps (e.g. Wearden, 1991a, 1992; Wearden & Towse, 1994, Experiment 1), and in these cases there may be only slight changes in task difficulty between conditions where, for example, the standard duration is varied over values of 500, 600, and 700 msec (Wearden, 1992, Experiment 3). If the steps remain 100 msec, then presumably non-standard stimuli close to the standard become more difficult to discriminate from it as the standard lengthens, as differences become a smaller proportion of the standard as this increases. However, available data suggest little effect on performance; for example, data from conditions with standard values of 400, 500, 600, and 700 msec superimpose well (Wearden, 1992, Figure 4, p. 139) when non-standard stimuli are spaced in 100-msec steps around the standard.

In addition to work on temporal generalization in humans, a substantial body of relevant data comes from experiments on *bisection*. Most methods used with humans derive from a technique introduced in an animal study by Church and Deluty (1977). In studies with humans, subjects are usually presented initially with examples of stimuli that differ in length, one being described as the short standard (S), the other as the long standard (L). After this, subjects receive series of stimuli (including S and L as well as intermediate durations) and must make different responses depending on whether they consider that the presented stimulus is more similar to S or to L. In studies from our laboratories (Wearden, 1991b; Wearden & Ferrara, 1995, 1996), no feedback is given after responses, whereas in others (e.g. Allan & Gibbon, 1991; Penney et al., in press) subjects are asked whether each stimulus *is* S or L, and feedback is provided on some trials. The different studies discussed below also differ in a number of other procedural factors, which will be described later.

The result of the procedures outlined above is a *psychophysical function*, the proportion of responses appropriate to one of the standard stimuli (usually L) plotted against stimulus duration. Psychophysical functions obtained from humans are almost always in the form of a monotonically increasing proportion of L responses as stimulus duration increases, from nearly zero L responses to the stimulus that is actually S, to nearly 100% to the stimulus that is actually L. The sensitivity of the timing process in bisection can be assessed by calculating the *Weber ratio* for the task. To do this (Maricq, Roberts, & Church, 1981; Wearden, 1991b), data points in the region of the psychophysical function that is steepest (and very close to perfectly linear) are used in linear regression, and the resulting regression equation is manipulated to find the durations that would give rise to 25%, 50%, and 75% L responses, according to the equation. The 50% value is the *bisection point*, and the *difference limen* is half the difference between the values giving rise to 75% and 25% L responses. The difference limen divided by the bisection point gives the Weber ratio, a measure of temporal sensitivity, where smaller values indicate more sensitive timing.

Intuitively, small Weber ratios correspond to psychophysical functions that change very steeply with changes in stimulus duration (indicating high sensitivity to time), whereas larger Weber ratios indicate less steep psychophysical functions (even over their steepest regions), and so a lower level of timing sensitivity.

Figure 2 shows Weber ratios from a number of different bisection studies with humans, calculated as described above, displayed against the ratio of the long and short standard durations (the L/S ratio). Although the difficulty of discrimination in bisection may not be fully captured by L/S ratio (e.g. $L - S$ difference may play some role in addition; see Wearden & Ferrara, 1996), at least part of task difficulty is captured by this simple measure. If the L/S ratio is large, the short and long standards are very easy to tell apart, whereas when this ratio is small, the different standards become more confusable.

The main focus of interest in the data shown in Figure 2 is any change in the Weber ratio as the L/S ratio varies within a particular experiment, as absolute differences in Weber ratios between experiments could be due to procedural differences (although in some cases different studies do produce very similar values). In all the data shown in Figure 2, Weber ratios declined as the L/S ratio became smaller, and this decline was completely systematic within studies, with one exception from Wearden and Ferrara

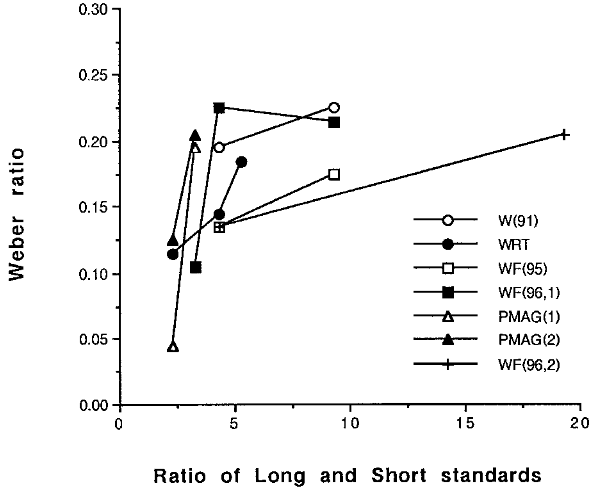

FIG. 2. Weber ratios from different experiments plotted against the ratio of the long and short standards used in the bisection task. The different experiments are identified by the key in the panel: W(91), Wearden (1991b); WRT, Wearden, Rogers, and Thomas (1997); WF(95), Wearden & Ferrara (1995); WF(96, 1 & 2), Wearden & Ferrara (1996) Experiments 1 & 2; PMAG (1 & 2), Penney et al., (in press), Experiments 1 and 2.

(1996), where a conditon with a 4:1 *L/S* ratio resulted in a slightly larger Weber ratio than obtained from a 5:1 condition. It is important to emphasize that the effect is obtained from bisection studies that employed different procedures, different absolute stimulus lengths, and different stimulus types. For example, Wearden (1991b) used unfilled short durations (defined by two clicks), whereas Wearden and Ferrara (1995, 1996) used short tones. Penney et al. (in press), and Wearden, Rogers, and Thomas (1997), on the other hand, used much longer stimulus durations (from 3 to 12 sec in Penney et al., and from 1 to 8 sec in Wearden et al., with chronometric counting prevented by a concurrent distracter task in the latter experiment), and in the Penney et al. study the same effect was obtained with auditory (Experiment 1) and visual (Experiment 2) stimuli. In addition, most studies used variants of the Church and Deluty (1977) bisection method, although Wearden and Ferrara (1995) also used a different technique, and feedback was provided in the Penney et al. experiments, but not in the others.

Another set of bisection data can be obtained from Allan and Gibbon (1991), where *L/S* ratios that were uniformly small and restricted to a narrow range (from 1.2:1 to 2:1) were used. In these cases, Weber ratios were very small (with all values being less than 0.10, and the modal value being about 0.06). The theoretical analysis used by Allan and Gibbon assumed that underlying timing sensitivity remained constant over this range (and this assumption was borne out by the good fit of their model to data, although results from one discrepant condition were not reported). However, close inspection of their data does suggest that the largest *L/S* ratio used did produce slightly flatter psychophysical functions than smaller ones, at least in some subjects (e.g. Allan & Gibbon, 1991, subject KC, Figure 9, p. 53). Overall, therefore, Allan and Gibbon's data do not seriously contradict the pattern of effects shown in Figure 2.

Thus, data from experiments on both temporal generalization and bisection in humans suggest that timing sensitivity, assessed by generalization gradients or Weber ratios, increases as the discrimination between stimuli relevant to the task (the standard and non-standard values in temporal generalization, *L*, *S* and intermediate durations in bisection) becomes more difficult. In both types of task, changes in timing may be slight or non-existent when difficulty is manipulated over a narrow range, but clearly different difficulty levels usually produced marked effects, as Figure 2 shows.

Variation in timing sensitivity with changes in task difficulty violates the requirement of superimposition and thus contradicts one of the basic principles of scalar timing, at least at first sight. The clear implication of our results is that something in the timing system varies in operation as the difficulty of the time discriminations required in the task varies, and exactly what the source of difference between conditions might be is discussed in the next section. Although the results presented and reviewed earlier do suggest a rare violation of scalar timing, the body of data overall in fact offers much support for it. In the Wearden et al. (1997) bisection study, for example, data superimposed well when absolute stimulus lengths were varied, provided that the L/S ratio was 4:1, so variation in absolute stimulus length by itself did not violate superimposition.

Overall, therefore, data from temporal generalization and bisection studies with humans support the view that more sensitive behavioural adjustment to duration values occurs under conditions of more difficult discrimination between the stimuli relevant to the task. In the next section, we discuss how such data might be treated theoretically.

Theories of Sensitivity Change

The factors that affect the slope of generalization gradients, and discrimination between stimuli in general, in discrimination learning studies with animals have attracted much interest over the last 40 or so years. Both Mackintosh (1974) and Honig and Urcuioli (1981) summarize this vast literature indicating that many manipulations can change the steepness of generalization gradients, ranging from the reinforcement schedule used to sustain operant responding to the degree of extinction of the conditioned response at the time of testing. An explanation often used for changes in discriminative sensitivity is that of "attention", in the specific sense of exposing animals to situations that force them to "attend to" (or have their behaviour brought under the control of) a particular stimulus dimension and ignore irrelevant competing dimensions. For example, the well-known effects of inter- and intra-dimensional discrimination training can be explained in this way (Mackintosh, 1974).

It is, however, unlikely that this use of "attention" can explain the current results, as verbally competent human subjects are instructed before the experiment begins that the relevant dimension of the stimuli is duration, and inspection of their data reveals no evidence at all that responding is controlled by anything else after such instruction. In the absence of irrelevant stimulus dimensions, it is thus difficult to see how humans can change their degree of "attention" to duration in the way that this term is used in explanations of animal discrimination learning. However, the word "attention" has another sense in everyday usage, which is perhaps more pertinent here—the idea of differential allocation of processing resources in different conditions; thus when we "pay particular attention", we allocate some sort of psychological resource so that the processing of an event is particularly precise, careful, and error-free (e.g. Kahneman, 1973). So, for example, in the timing tasks discussed above, difficult conditions cause subjects to process durations more carefully than they do in "easy" conditions, so time discrimination becomes more sensitive. We will return to this issue of attentional explanations of our effects after examining some quantitative models used to treat data from humans in the context of scalar timing.

In a number of experiments (Wearden, 1992; Wearden, Denovan, Fakhri, & Haworth, in press a; Wearden & Towse, 1994; Wearden et al., in press b) data from temporal generalization experiments with humans have been treated by a theoretical variant developed by Wearden (1992) from an account of temporal generalization in rats provided by Church and Gibbon (1982). They proposed that the temporal generalization gradients produced by their rats arose from a comparison of a short-term memory representation of the duration just presented with a longer-term representation of the standard duration. If the duration just presented is "close enough" to the standard the subject responds, otherwise it does not. Specifically, Church and Gibbon proposed that rats respond when

$$\mathrm{abs}(s^* - t)/s^* < b^*$$

where s^* is a sample randomly drawn from the memory of the standard duration, represented as a Gaussian distribution with accurate mean, s, and some coefficient of variation, c; t is the duration just presented, assumed to be timed without variance; and b^* is a random value drawn from a Gaussian distribution of a threshold with mean b and standard deviation, x, and *abs* indicates absolute difference. Both s^* and b^* vary from trial to trial; thus behaviour can vary from trial to trial even when the standard duration and the duration just presented remain constant. The above equation will generate symmetrical generalization gradients, so in order to produce the usually markedly asymmetrical generalization gradients found in studies with humans, some modification of Church and Gibbon's model is necessary. Wearden (1992) proposed that humans identify a stimulus as the standard when

$$abs(s^* - t)/t < b^*$$

where all terms are as in Church and Gibbon's original model.

This modified Church and Gibbon model (MCG model) fitted asymmetrical generalization gradients well in both Wearden (1992) and Wearden and Towse (1994). The essential difference between the MCG model and that applied to rats is a slight difference in the decision process, as the absolute difference between the just-presented stimulus and the standard is expressed as a fraction of the just-presented duration, rather than as a fraction of the standard. The MCG model has three parameters: c, the coefficient of variation of the memory representation of the standard; b, the threshold mean; and x, the standard deviation of the threshold. A focus of theoretical interest in the application of the MCG model to data from the present study was how the parameter values might vary when fitting data from conditions in which the closeness of spacing of stimuli around the standard was varied, such as comparisons of data from the lin150 and lin75 groups, and the logA and logB groups.

A priori, there were a number of possibilities. One of these was that the main difference between the parameter values needed to fit data from the different groups would be in *c*, the memory variance parameter. Such a difference would imply that, for some reason, the precision of the memory of the standard 600-msec duration varied between groups, being, for example, less variable in conditions with closer stimulus spacing. On the other hand, another possibility is that the main difference between conditions, according to fits of the MCG model, would lie in parameter values concerned with the threshold, *b*, such as its mean and standard deviation. In psychological terms, this would mean that the average threshold value for making the response that the stimulus just presented was indeed that standard was, for example, lower with closer stimulus spacing, so that subjects were more conservative about making the YES response in conditions with closer stimulus spacing.

We applied the MCG model to data from the various conditions presented in the experiment described above (Figure 1). To produce each fit, a TurboPascal computer program simulated 300 trials (the same number as produced by the subjects) of judgements of each stimulus in each group. The parameters varied were *c* (the coefficient of variation of the memory representation of the standard), *b* (the mean threshold value), and *x* (the standard deviation of the threshold). The values of two of these parameters (*c* and *b*) were varied over a wide range, and for each set of values the mean absolute deviation (MAD), the average absolute deviation between the values predicted by the model and the obtained data, was calculated, and the parameter values were changed until the smallest MAD value was obtained. The *x* parameter was kept constant at 0.5*b*, as both previous work and fits to the present data suggested that little improvement in fit was obtained by using other values.

The correspondence between fits of the MCG model and data are shown in Figure 3. Consider first fits to data from the lin150 and lin75 groups. For the lin150 group, the best-fitting parameters (*c*, *b* and *x*) were 0.30, 0.22, and 0.11, with an MAD of 0.02. However, Figure 3 shows that the theoretical curve produced using these values did not fit data from the lin75 group at all well. In this latter condition, the best-fitting values were 0.28, 0.14, and 0.07 (MAD = 0.03). Thus, the main difference between the parameter values needed for the lin150 and lin75 conditions was that the threshold value for the YES response was much lower in the lin75 condition.

Also shown in Figure 3 are data from the logA and logB groups. Parameter values for logA condition were 0.3, 0.20, and 0.10 (MAD = 0.03), and the values for logB were 0.3, 0.14, 0.07 (MAD = 0.04). Once again, it was clear that using the parameter values from the fits to the wider spacing condition (logA) produced a poor fit to data from the more closely spaced condition, which itself was fitted by the MCG model with a smaller mean threshold.

From the perspective of the MCG model, therefore, it seems that the difference in steepness between the temporal generalization gradients obtained when stimulus spacing around a constant standard value was varied was largely due to smaller threshold values, implying more conservative decisions about responding YES when the stimulus spacing was narrower. The memory representations of the standard duration in the compared conditions differed little, if at all, with stimulus spacing, suggesting that the representation

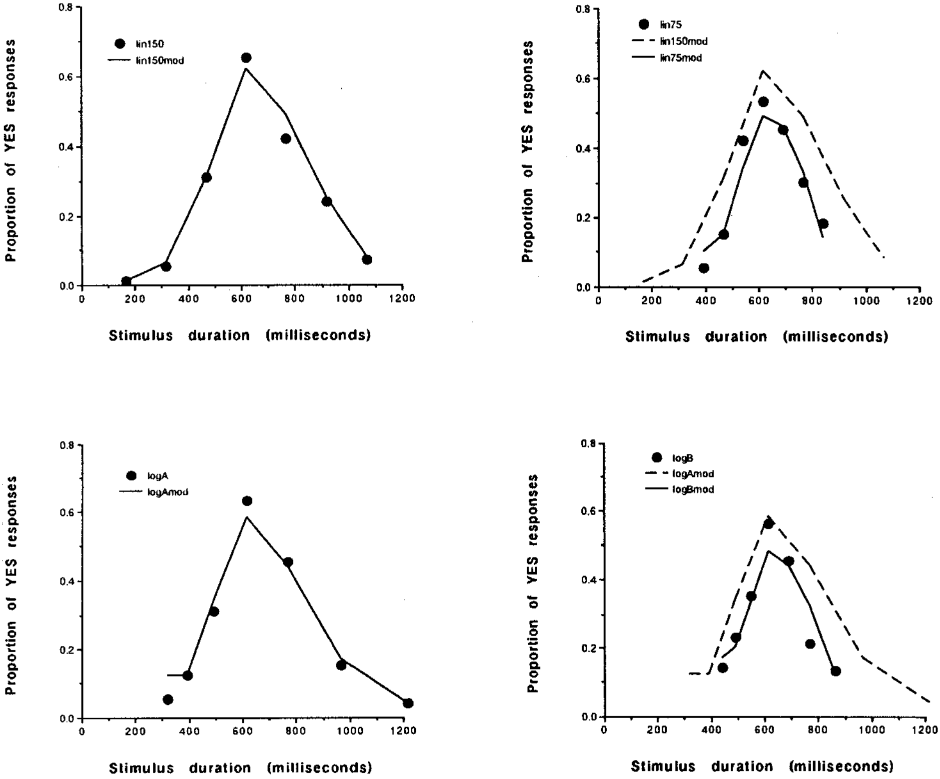

FIG. 3. Data points (filled unconnected circles), and predictions of the MCG model (solid or dashed lines) fitted to data. lin150, lin75, logA, and logB identify data points; lin150mod, lin75mod, logAmod, and logBmod show predictions of various MCG models.

of the 600-msec duration hardly differed at all in the different groups. In general, the MCG model fitted data reasonably well (particularly in the linear spacing conditions), with most deviation coming from a single data point. Overall, the fits of the MCG model here had about the same degree of accuracy as in previous studies, such as Wearden (1992), Wearden and Towse (1994), and Wearden et al. (in press b).

The explanation of changes in behavioural timing sensitivity in terms of threshold is, unfortunately, impossible to apply to studies of bisection, where, as we have seen, varying the *L/S* ratio appears to vary the Weber ratio systematically (Figure 2). The problem is that current models of bisection do not use threshold comparison processes that govern overall level of responding to stimuli, as in temporal generalization, but, rather, employ what might be better termed *bias* parameters (see Allan & Gibbon, 1991, and Wearden, 1991b, for different types of bias). These bias parameters do not affect the *slope* of the psychophysical function but, instead, alter the balance of responding between the two possible responses to a stimulus, short and long.

Consider, for example, the psychophysical functions from bisection shown in Figure 4, which come from a simulation described later. The effect of varying bias would be to shift the whole psychophysical function to the left or to the right (thus varying the proportion of long responses occurring to each presented stimulus) rather than affecting its slope. Effects on slope, which are the type of performance changes that occur in data when L/S ratio is varied (Figure 2), can be simulated by changing the *memory representations* of S and L or, more generally, the variability of representations of timed stimuli.

This can be illustrated with a simple difference model, which does not employ a bias term. The standards S and L in a bisection task are represented as Gaussian distributions, with accurate means S and L, and scalar variance, so that the standard deviation of the S distribution is cS, and that of the L distribution cL, where c is some coefficient of variation. On each trial, some stimulus of length t, assumed to be timed without error, is presented, and this value is compared with samples (s^* and l^*) drawn randomly from the memory distributions of S and L. An L response occurs if the absolute difference between l^* and t is less than that between s^* and t, and an S response occurs otherwise.

This model is similar to, but slightly simpler than, that used by Wearden (1991b) to fit data from bisection studies in humans, but the main focus of interest here is on how changes in c, the coefficient of variation of the memory of S and L, affect the psychophysical function produced by the model. To show this, we simulated a typical bisection task in humans with $S = 200$ msec and $L = 800$ msec, with other stimuli spaced in 100-msec steps between S and L (as in Wearden, 1991b, and Wearden & Ferrara, 1995, for example). Figure 4 shows the resulting psychophysical functions, averaged over 1,000 trials with each stimulus value, with c varied over values of 0.15, 0.25, 0.35, and 0.40—values that span the range of those used to fit experimental data (e.g. Wearden, 1991b).

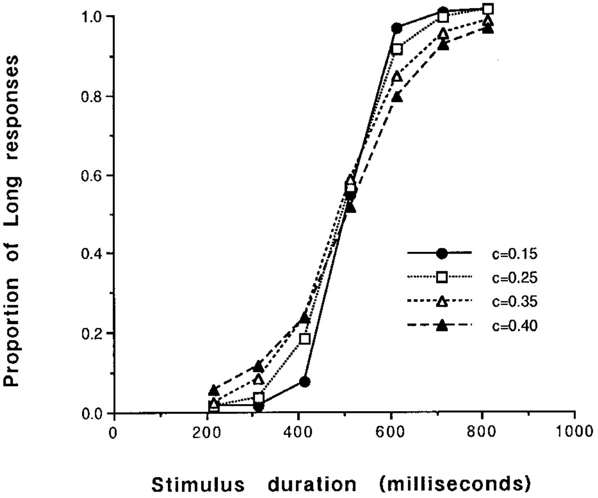

FIG. 4. Proportion of long responses plotted against stimulus duration produced by the simple difference model discussed in the text. The key identifies the coefficient of variation (c) of the memory representations of the short and long standards used for the different simulations.

The simple difference model illustrates the effects of *c* on the psychophysical function, and in this respect it is representative of more complex models that use different decision rules, such as those of Allan and Gibbon (1991) and Wearden and Ferrara (1995). In these models, likewise, increasing the underlying coefficient of variation of the representation of the *S* and *L* (or the mean of all the stimuli used in the task in Wearden & Ferrara, 1995) will flatten the psychophysical function. The stimulus values, bias effects, and other technical details of the simulation are not critical for illustration of this point, nor do other predictions of the different models, such as the location of the bisection point, affect the influence of *c* on the steepness of the psychophysical function.

It is clear from inspection of Figure 4 that the steepness of the psychophysical function varies systematically with *c*, increasing in steepness (i.e. smaller Weber ratio) as *c* decreases. This relation is not surprising, as both the Weber ratio and *c* are measures of timing sensitivity and so should vary together, but it does illustrate a way in which the results shown in Figure 2 could be explained: the memory representation of the standard *S* and *L* stimuli in bisection could become less variable (i.e. smaller *c*) as the *L*/*S* ratio decreases, so standards are more precisely represented on more difficult bisection tasks. Although this idea would fit data, there are a number of problems with it. For one, this result (change in memory representation) is not compatible with the MCG analysis of discrimination difficulty effects in temporal generalization presented earlier (e.g. Figure 3), where it was found that the memory representation of the standard did not change. For another, it represents a serious violation of the principles of scalar timing, by assuming that the putatively constant memory representations of durations change systematically with task variables. Finally, the problem arises of what causes the changes in variance of representations of *S* and *L*.

An approach to these problems might be derived from recent work suggesting that the speed of the pacemaker of the pacemaker–accumulator clock in humans can be affected by arousal manipulations, with conditions provoking increases in arousal causing the pacemaker to run faster (e.g. Penton-Voak et al., 1996; Treisman, Faulkner, Naish, & Brogan, 1990; Wearden & Penton-Voak, 1995). Most quantitative theories of how pacemakers operate require that faster pacemaker speed produces less variable time representations (e.g. see the discussion of Poisson pacemakers in Gibbon, 1977, and Killeen & Fetterman, 1988), although not necessarily shorter or longer ones on average. If we suppose that more difficult bisection conditions are more arousing than are easier ones, then the faster pacemaker resulting from this arousal difference will produce less variable representations of all stimuli (*S*, *L*, and all *t*), and this will change timing variance in the direction needed to account for effects of discrimination difficulty on bisection like those illustrated in Figure 2. However, this reasoning assumes that pacemaker speed is a major determinant of variance in the timing system, whereas the usual treatment of data by scalar timing theory assumes that it contributes only slightly to overall data variance (e.g. Gibbon, 1992), with the majority of variance arising from the memory representations of *S* and *L*.

On the other hand, it may be that for bisection long-term memory representations of *S* and *L* are less important for humans than for animals (for data from which the theory of bisection was originally developed, see Gibbon, 1981) and that performance may be more influenced by short-term representations of events that are derived directly from the accumulator of the internal clock (e.g. see Rodriguez-Girones & Kacelnik, 1995). This idea might also help to address other problems, such as why increasing age and decreasing IQ, which both increase the variance of the reference memory for the standard duration on a temporal generalization task, have no effect on bisection performance (Wearden et al., in press b). Obviously, deterioriation in reference memory may have no consequences if this memory is not used in bisection with humans.

Attentional ideas (with "attention" used in the sense of allocation of resources rather than selection, e.g. Kahneman, 1973) might also form a basis for explaining some of the effects proposed above. There is evidence that increasing attention to time can change duration judgements, both affecting the mean (e.g. Grondin & Macar, 1992; Macar, Grondin, & Casini, 1994) and changing timing variability (Brown & West, 1990; Brown, Stubbs, & West, 1992). For example, Brown et al. showed that requiring subjects to time multiple overlapping events rather than a single one not only decreased performance accuracy, but also increased performance variability in ways that suggested that timing variability was increased in the multiple timing task. Similarly, using a pardigm in which subjects were instructed to allocate attention differentially to the duration of a stimulus rather than its intensity, or vice versa, Grondin and Macar (1992) found generally shorter duration judgements when attention was directed away from timing (see also Macar et al., 1994).

The mechanism by which such attentional effects are mediated remains at present unclear. Grondin and Macar (1992) and Macar et al. (1994) proposed that directing attention away from duration causes pulses from the pacemaker of a pacemaker–accumulator clock to be missed, thus shortening mean duration judgements, and one possible related hypothesis is that fluctuations in attention from one trial to another cause differential numbers of pulses to be missed between trials, thus inflating the variability of time representations compared to a condition in which attention remains constant. However, an alternative explanation of Grondin and Macar's result is that directing attention towards duration increases pacemaker speed, and directing attention away decreases it, producing consequent shifts in mean and variance of time representations, although available data from experiments using attentional manipulations cannot at present decide between these two suggestions.

Allan (1992) discusses possible effects of attention on the *switch* connecting the pacemaker to the accumulator of the internal clock. High levels of attention might cause the switch to close and open with shorter latency than lower attentional levels, but if the latencies to close and open are equally affected by an attentional manipulation, neither the mean number of pulses accumulated during the timing of an event nor the variability of timing will be affected. To produce the changing variability of time representations that seem to be needed to account for bisection data, it would be necessary to assume that attentional effects produced changes in the *variability* of switch operation. For example, if the subject was paying little attention to a stimulus, its offset and onset might be "blurred" because of increased switch variance, whereas if the subject was highly attentive, switch variance would be reduced. An analogous role for switch variance has been proposed by Wearden, Edwards, Fakhri, and Percival (submitted) to account for differential timing variance when auditory and visual stimuli of the same real duration are judged.

Taken overall, the results presented in this article and the data from other experiments reviewed strongly suggest that some liberalization of the mechanisms of standard scalar timing theory, such as arousal-sensitive changes in pacemaker speed (Penton-Voak et al., 1996), might allow the theory to account for a much wider range of data from human subjects than was previously possible (see Zakay & Block, 1995, for a model of this sort). Another modification might be to allow ‘‘attentional’’ manipulations to modulate the pacemaker, the switch, the memory for stimulus durations, the comparison processes used in the task, or combinations of all these. As well as the present article, increasing interest in attention to time has been recently reflected in Macar et al. (1994) and Penney, Holder, and Meck (1996), with the latter study discussing the role of attention in animal timing. Developing scalar timing theory to encompass attentional and arousal effects and so extend its range while at the same time retaining the precision for which it has become well known presents a significant challenge for the future.

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Modification de la sensibilité pour la durée et temps scalaire chez l'homme: une expérience, une revue de question et quelques explications.

Des données obtenues à partir d'un certain nombre de recherches réalisées chez l'homme avec des tâches de généralisation temporelle et de bissection, suggèrent que la sensibilité de l'ajustement au temps augmente lorsque la tâche exige la discrimination de stimuli plus rapprochés. Une expérience de généralisation a montré cet effet, la discrimination entre une durée standard de 600 ms et des durées non-standards plus courtes et plus longues étant meilleure lorsque les durées non-standards sont moins espacées temporellement autour des 600 ms. Une revue de la littérature a relevé des effets similaires dans d'autres tâches de généralisation temporelle, et aussi dans un certain nombre de tâches de bissection, où la discrimination temporelle est améliorée lorsque le rapport entre les standards Long et Court décroît. Un modéle standard de généralisation temporelle chez l'homme a permis d'expliquer les données en termes d'une diminution du seuil de réponse, plutôt qu'en termes d'un changement de la représentation de la durée standard. A l'inverse, les données de bissection ont pu être modélisées sur la base d'une représentation plus précise des standards Long et Court dans les condtions les plus difficiles. Des explications de certains effets en termes d'attention portée à la durées et/ou de changements du débit de l'horloge interne induits par l'éveil ont été discutées.

Cambios en la sensibilidad a la duración en la temporización escalar en humanos: un experimento, una revisión y una posible explicación

Pruebas recogidas en varios experimentos sobre temporización en humanos, utilizando tareas de bisección y de generalización temporal, muestran un ajuste conductual más sensible a las duraciones presentadas bajo condiciones en las que la tarea de temporización requiere la discriminación entre estímulos más próximos entre sí en la dimensión de duración. Este efecto se demostró en un experimento de generalización temporal, al observarse que la discriminación entre una duración típica de 600 msegs y estímulos atípicos de mayor y menor duración fue mejor cuando los estímulos atípicos se agrupaban en torno a los 600 msegs. La revisión de la literatura anterior muestra efectos similares en otras tareas de discriminación temporal y en varios estudios de bisección, en los que la discriminación temporal mejoró a medida que descendía la razón de duraciones largas y cortas en las tarea de bisección. Un modelo típico de lar generalización temporal en humanos explica los datos experimentales en términos de una reducción del umbral de respuesta bajo las condiciones más difíciles y no como consecuencia de un cambio en la representación de la duración típica. Por el contrario, los datos de los experimentos de bisección pueden ser modelizados a partir del supuesto de que las representaciones de las duraciones típicas cortas y largas son màs precisas bajo las condiciones màs difíciles. Finalmente, se comentan las explicaciones de algunos de estos efectos en términos de atención a la duración y/ó cambios inducidos por el nivel de activación en la velocidad del reloj interno.