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Stimulus Range Effects in Temporal Bisection by Humans

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Two experiments with human subjects, using short-duration tones as stimuli to be judged, investigated the effect of the range of the stimulus set on temporal bisection performance. In Experiment 1, six groups of subjects were tested on a temporal bisection task, where each stimulus had to be classified as "short" or "long". For three groups, the difference between the longest (L) and shortest (S) durations in the to-be-bisected stimulus set was kept constant at 400 msec, and the L/S ratio was varied over values of 5:1 and 2:1. For three other groups, the L/S ratio was kept constant at 4:1 but the $L - S$ difference varied from 300 to 600 msec. The bisection point (the stimulus value resulting in 50% "long" responses) was located closer to the arithmetic mean of L and S than the geometric mean for all groups except that for which the L/S ratio was 2:1, in which case geometric mean bisection was found. In Experiment 2, stimuli were spaced between L and S either linearly or logarithmically, and the L/S ratio took values of either 2:1 or 19:1. Geometric mean bisection was found in both cases when the L/S ratio was 2:1, but effects of stimulus spacing were found only when the L/S ratio was 19:1. Overall, the results supported a previous conjecture that the L/S ratio used in a bisection task played a critical role in determining the behaviour obtained. A theoretical model of bisection advanced by Wearden (1991) dealt appropriately with bisection point shifts discussed above but encountered difficulties with stimulus spacing effects.

The technique of *temporal bisection* has been one of the most commonly used methods for the study of animal timing (e.g. Church & DeLuty, 1977; Maricq, Roberts, & Church, 1981; Meck, 1983; Platt & Davis, 1983; Raslear, 1983, 1985). Although some studies (e.g. Platt & Davis, 1983) use different methods, most have followed the technique originally developed by Church and Deluty (1977) which, in schematic form, is as follows: An animal subject is reinforced for making one response (e.g. a press on the left lever of a standard operant chamber) after a stimulus of a certain length (e.g. 2 sec), defined as the

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standard short stimulus (*S*), and another response (e.g. on the right lever) after a longer stimulus (e.g. 8 sec long, a standard long stimulus, *L*). If *S* and *L* are sufficiently different, as they are with the example values given above, this discrimination is not difficult for rats and pigeons, who come to emit more than 90% correct responses after a few sessions of training. What "sufficiently different" means in the context of temporal bisection is discussed more fully in the paper.

After training, subjects receive stimuli that differ in length between (and usually including) *S* and *L*, and the response to each stimulus (which is unreinforced) is noted. The near-universal finding is a monotonic increase in the number of "long" responses (i.e. the response that would have been reinforced after *L*) with increases in stimulus length. The psychophysical function relating proportion or number of "long" responses to stimulus length is of ogival shape, ranging from zero or just a few percent of "long" responses when *S* is actually presented to 90% or more when *L* is presented. One focus of experimental interest has been the location of the *bisection point*, the stimulus value giving rise to 50% "long" responses, and most studies using animal subjects agree that this is located at the *geometric mean* of *S* and *L*—that is, the square root of the product of *S* and *L*, 4 sec with the example values used above.

Many of the studies of bisection in animals have been inspired by, or related to, *scalar timing* theory (Gibbon, 1977; Gibbon, Church, & Meck, 1984), currently the leading theory of animal timing, and there has been some recent interest in the application of this theory to timing in humans (for a non-technical review see Wearden & Lejeune, 1993). The method of Church and Deluty (1977) can easily be adapted to produce techniques for studying temporal bisection in humans (as in Allan & Gibbon, 1991; Wearden, 1991, 1993; Wearden & Ferrara, 1995), and these quickly produce very orderly data. Unfortunately, there are some disagreements about the characteristics of temporal bisection performance in humans. These can be summarized in terms of two issues, and the first of these is the location of the bisection point. As noted above, studies with animals with only a few exceptions (which are discussed later in this article) find this bisection point at the geometric mean of *S* and *L*, and Allan and Gibbon (1991) duplicated this result with humans. On the other hand, work by Wearden (1991) and Wearden and Ferrara (1995) found that the bisection point was better described as being closer to (usually just less than) the arithmetic mean of *S* and *L*, rather than nearer to the geometric mean.

A second issue is whether the spacing of non-standard stimuli between a constant *S* and *L* makes a difference to bisection performance. Most animal studies (as reviewed in Wearden and Ferrara, 1995) find that stimulus spacing makes no difference: for a constant *S* and *L*, the number of "long" responses made to some intermediate stimulus, *t*, is not affected by the other non-standard stimuli around *t*. This result was also duplicated by Allan and Gibbon (1991), at least in the sense that arithmetic or geometric stimulus spacing between a constant *S* and *L* made little obvious difference to bisection performance. On the other hand, Wearden and Ferrara (1995) found large and clear effects of stimulus spacing in some of their conditions. For example, when *S* was 100 msec and *L* 900 msec, the psychophysical function was shifted markedly to the left when intermediate stimuli were logarithmically spaced compared with arithmetic spacing. The effect was much smaller, or non-existent, when the L/S ratio was smaller (4:1).

There were numerous procedural differences between the studies of Allan and Gibbon (1991) and those of Wearden (1991) and Wearden and Ferrara (1995), which prompt the pessimistic conclusion that bisection performance in humans is highly susceptible to small procedural changes, and that it will be difficult to draw any coherent conclusions about it. However, Wearden and Ferrara (1995) found that bisection performance was robust in their studies in the face of a number of procedural variants, suggesting that some resolution of the conflicting results might be possible, even when methods used for temporal bisection vary between studies. Wearden and Ferrara (1995) examined the temporal bisection literature, including experiments with both humans and animals, and suggested that a critical variable operating in the different studies was the relative value of S and L, expressed either as the $L - S$ difference or as the L/S ratio. When L and S were close together, the bisection point was located at the geometric mean, and stimulus spacing effects were small or absent. On the other hand, when L and S were far apart, the bisection point was located at or near the arithmetic mean, and effects of stimulus spacing were found. If the close or far relation is expressed as the L/S ratio, values of 2:1 or less (as used by Allan & Gibbon, 1991) appear to produce geometric mean bisection and absence of stimulus spacing effects in humans; values greater than 2:1 (as used in Wearden, 1991, and Wearden & Ferrara, 1995) produce the other pattern of results. In studies with animals, on the other hand, values of 4:1 can still produce geometric mean bisection.

The aim of the present article is to report data relevant to this stimulus range conjecture, which, more specifically, states that small L/S ratios (or $L - S$ differences) should produce evidence for geometric mean bisection and absence of stimulus spacing effects, whereas large L/S ratios should produce arithmetic mean bisection points (or bisection points close to the arithmetic mean) and evidence for spacing effects. It should be noted that this proposal is advanced on the basis of observation of apparent regularities in previous data (as discussed by Wearden & Ferrara, 1995). It is not a prediction that derives from any formal theory of bisection and, indeed, as will be discussed later, may provide a challenge for current theories if found to be supported.

As L and S become more different, both the L/S ratio and $L - S$ difference increase, and it is unclear in which terms the psychological difference of L and S is better expressed, although data from some animal experiments indicate very similar bisection performance when the L/S ratio is constant and the $L - S$ difference varies (see Church & Deluty, 1977, and Maricq et al., 1981). Experiment 1 below thus investigated the bisection performance of humans faced with six different stimulus ranges. In three of these, the L/S ratio remained constant at 4:1 but the $L - S$ difference varied; for the other three, the $L -$ S difference remained constant but the L/S ratio varied, from 5:1 to 2:1. The spacing of non-standard stimuli between L and S was arithmetic in all cases, so the focus of interest in Experiment 1 was on possible variation in the location of the bisection point with respect to the two putative candidates (the geometric and arithmetic means) as the stimulus range varied.

In all procedural details the present study closely followed the *partition method* of bisection used by Wearden and Ferrara (1995). In this method, which closely resembles the classical method of constant stimuli, no specific stimulus in the to-be-bisected set is identified as a standard, either "short" or "long". Subjects simply receive repeated presentations of the whole stimulus set, with the members arranged in different random orders, and have to classify each stimulus as "short" or "long", using whatever criteria they wish to employ. The whole stimulus set is repeated 20 times, and data are taken from the last 10 repetitions. Wearden and Ferrara (1995) found that this method produced data very similar to those obtained with the Church and DeLuty (1977) variant used by Wearden (1991).

EXPERIMENT 1

Method

Subjects

Seventy-two Manchester University undergraduates, participating for course credit, were arbitrarily allocated to six equal-sized groups.

Apparatus

A Hyundai TSS8C personal computer (IBM compatible) controlled all experimental events. The computer keyboard served as the response manipulandum. All stimuli in the sets to be bisected were 500-Hz tones produced by the computer speaker. The experiment was controlled by a Turbo Pascal program, but specially written routines derived from assembly language were used to time the stimuli, which were timed to an accuracy of at least 1 msec.

Procedure

The procedure for all groups was identical except for the stimuli in the to-be-bisected set. Each group received a different stimulus set, with values shown in Table 1.

For three groups (D1, D2, and D3), the difference between the shortest (S) and longest (L) stimulus in the set used varied, but the L/S ratio remained constant at 4:1. For the other three groups (R1, R2, and R3), the difference between L and S remained constant at 400 msec, but the L/S ratio varied, over values of 5:1 – 2:1.

All subjects received a single experimental session, lasting from 15 to 20 min, conducted as follows: Subjects started the experiment by pressing the spacebar after an appropriate prompt appearing on the screen, then presented each trial by again pressing the spacebar after a *Press spacebar for next trial* prompt. A stimulus presentation then followed after a delay that was a value randomly chosen from a uniform distribution ranging from 1 to 3 sec. Each stimulus set (i.e. D1 to

TABLE 1
Stimulus Values Used for the Six Different Groups in Experiment 1

Group	*Stimulus Values*							$L - S$	L/S
D1	100	150	200	250	300	350	400	300	4:1
D2	150	225	300	375	450	525	600	450	4:1
D3	200	300	400	500	600	700	800	600	4:1
R1	100	167	233	300	367	433	500	400	5:1
R2	200	267	333	400	467	533	600	400	3:1
R3	400	467	533	600	667	733	800	400	2:1

Note: Also shown are $L - S$ difference (in msec), and L/S ratio. Stimulus values are given in msec.

D3, or R1 to R3—see Table 1 for the values) was presented 20 times, with each of the 20 series involving presenting the stimuli in the set in a different random order. After each stimulus presentation, subjects were required to classify each presented stimulus either as "short" or "long" by pressing appropriate keys on the computer keyboard. As there is no "right answer" on the task, no feedback was given after the response. Subjects had previously been told that all stimuli had durations of less than 1 sec, but that some tones would be clearly shorter than others. Data were collected from the last 10 presentations of each stimulus set.

Results and Discussion

Figure 1 shows the mean proportion of "long" classifications of each stimulus, plotted against stimulus duration, for each of the six groups used in Experiment 1. Data points are shown as unconnected filled circles, and the line fitted to them comes from a theoretical model to be discussed later.

Inspection of data in the different panels of Figure 1 immediately reveals that the method used produced orderly data in all the groups, with the proportion of "long" responses rising, usually monotonically, from near-zero "long" responses at S to near 100% at L, as stimulus length increased. This pattern of results very closely resembles that obtained in previous bisection experiments with human subjects (e.g. Wearden, 1991, 1993; Wearden & Ferrara, 1995).

The bisection point—the stimulus value that would yield 50% "long" responses—was calculated by three different methods, as by Wearden and Ferrara (1995), and results are shown in Table 2. Each method used the psychophysical function of the proportion of "long" responses versus stimulus duration (i.e. plots in the form shown in Figure 1) as its basis. Mean interpolation (MINT) used the averaged psychometric function to interpolate the bisection point by eye; the individual interpolation method (IINT) performed an identical operation on the psychometric functions of individual subjects, then averaged out the resulting bisection points. The regression method (REG), used originally by Maricq et al. (1981) and followed by Wearden (1991), used linear regression of the data points yielding the line of steepest slope. The resulting regression line was then used to calculate the bisection point. Table 2 shows the bisection points, as well as the arithmetic and geometric means of S and L, for comparison.

Allan and Gibbon (1991) suggested that the bisection point might in some cases not be located exactly at the geometric mean, but at some consistent fraction of this mean. One way of testing this suggestion is to divide the bisection points by the geometric mean value, thus expressing the bisection points as some fraction of the geometric mean, with values greater than 1.0 indicating bisection points above the geometric mean and values lower than 1.0 below it. The results of this calculation are shown in Table 2, as K_1 values. It is also possible that the bisection points are some consistent fraction of the arithmetic mean, and the K_2 values shown in Table 2 test this suggestion in a similar manner.

Several points are obvious on inspection of the values given in Table 2. (1) The three different methods used to calculate the bisection point yielded values within a few msec of each other (a result also obtained by Wearden & Ferrara, 1995), and so could be aggregated to produce a mean, suggesting that the method used to calculate the bisection point makes little difference to the outcome of the calculation. (2) For most groups, the

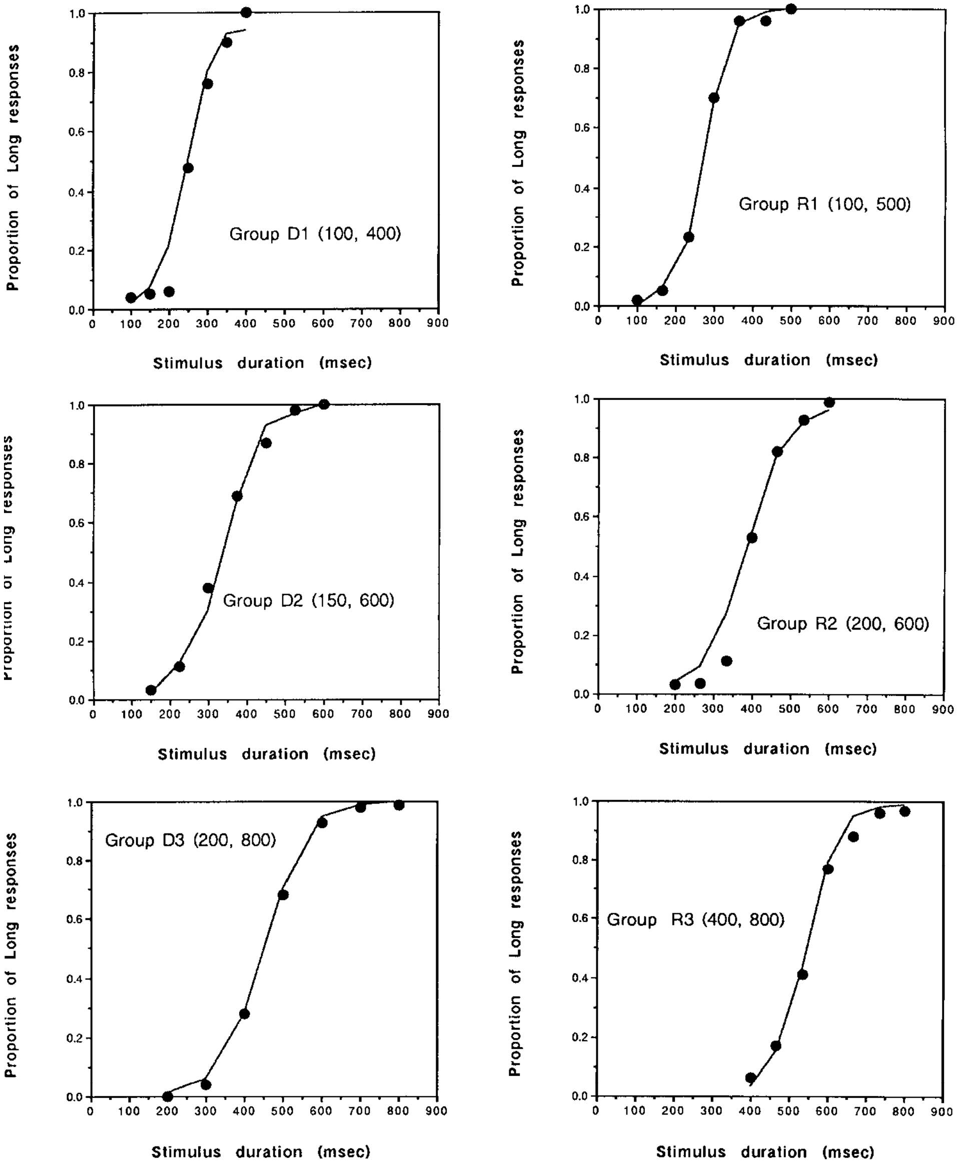

FIG. 1. Proportion of "long" responses plotted against stimulus duration, shown as unconnected filled circles, for the six groups of Experiment 1. The text within each panel shows the group identifier and the shortest and longest stimulus (values in msec) in the to-be-bisected set. The continuous line in each panel indicates the best-fitting theoretical values generated by the modified difference model discussed in the text, with parameter values shown in Table 3.

TABLE 2
Bisection Points Calculated According to the Three Different Methods and the Mean of All Three for the Six Different Groups of Experiment 1 and the Four Different Groups of Experiment 2

Group	*GM*	*AM*	*MINT*	*IINT*	*REG*	*MEAN*	K_1	K_2
Experiment 1								
D1	200	250	260	264	264	263	1.31	1.05
D2	300	375	355	356	353	355	1.18	0.95
D3	400	500	460	463	457	460	1.15	0.92
R1	224	300	300	294	291	295	1.32	0.98
R2	364	400	400	412	407	406	1.12	1.01
R3	566	600	550	551	550	550	0.97	0.92
Experiment 2								
LIN50	218	500	458	458	460	459	2.10	0.92
LOG50	218	500	301	286	298	295	1.35	0.59
LIN450	636	675	645	642	643	643	1.01	0.95
LOG450	636	675	626	648	627	634	1.00	0.94

Note: MINT: mean interpolation; IINT: Individual interpolation; REG: Regression

Also shown are the geometric (GM) and arithmetic (AM) means of *S* and *L*. K_1 is the mean bisection point divided by GM, K_2 the bisection point divided by AM. Values greater than 1.0 indicate that the bisection point was greater than GM or AM; values less than 1.0 indicate that the bisection point was smaller.

bisection point, however calculated, was closer to the arithmetic mean of *S* and *L* than to the geometric mean; for example, almost all K_2 values were closer to 1.0 than were K_1 values, (where K_1 and K_2 are as described above). In general, this finding replicates those obtained in previous bisection experiments we have conducted with humans (Wearden & Ferrara, 1995; see also Wearden, 1991, 1993). The exception to this generalization came from group R3, which had the smallest *L*/*S* ratio, 2:1. In this case, the bisection point was not only much closer to the geometric mean than to the arithmetic mean but, uniquely in the stimulus ranges we used in Experiment 1, was actually slightly below the geometric mean.

A common result in studies of human timing inspired by scalar timing theory is conformity of data to *Weber's law*, the requirement that the sensitivity of timing remains constant as the absolute durations timed vary. Some data manifest such Weberian properties directly (e.g. Wearden & McShane, 1988), but in other studies Weber's law is tested by examining the property of *superimposition* (also called *superposition*), the finding that data from different conditions superimpose when response measures are plotted against time expressed on some relative scale (e.g. see Church & Gibbon, 1982). Allan and Gibbon (1991) discuss the appropriate method of testing superimposition in bisection experiments (pp. 45–46) and advocate plotting the proportion of "long" responses against stimulus duration, where stimulus duration is expressed as a fraction of the bisection point appropriate for the condition plotted. This type of manipulation allows data sets with different *L*/*S* ratios to be directly compared, because if Weber's law holds, the proportion of "long" responses from all conditions should superimpose when plotted in this way.

We treated the psychophysical functions from the six groups of Experiment 1 in this way, using the mean bisection point (MEAN in Table 2) for each condition as a divisor for the stimulus durations, and results are plotted in Figure 2. Inspection of Figure 2 shows that superimposition was clearly manifested in our data, indicating that our bisection procedure produced constant-sensitivity Weberian timing. Comparison of our Figure 2 with superimposition data from Allan and Gibbon (1991, their Figures 5 and 9) suggests that the quality of superimposition in our Experiment 1 was about equal to theirs.

Data from Experiment 1 clearly supported Wearden and Ferrara's (1995) conjecture that the range of the stimulus set used plays some role in determining the location of the bisection point in studies of temporal bisection with humans. Inspection of data in Table 2 also suggests that range effects are better expressed in terms of the L/S ratio than the $L - S$ difference. Although the bisection point did decline relative to the arithmetic mean of S and L, suggesting some effect of $L - S$ difference (e.g. comparisons of groups D1, D2, and D3), it only reached the geometric mean of S and L when the L/S ratio was at its lowest (in group R3). Although our data are not conclusive as to how the difference between "short" and "long" standards should be represented in terms of difference or ratio, ratios do have clearer effects, and using ratios to represent the difficulty of the time discrimination task has been proposed in previous studies with humans (e.g. Allan & Gibbon, 1991). Furthermore, studies with animals have found no clear effects of the $L - S$ difference on bisection performance when the L/S ratio was kept constant (e.g. Church & Deluty, 1977; Maricq et al., 1981). Ideally, this issue would be examined experimentally by using a wider range of differences and ratios than we have used, but certain problems arise. For example, having a large $L - S$ difference while maintaining a small L/S ratio necessitates using longer-duration stimuli than we have used (such as stimuli several seconds long), and human subjects would almost certainly employ chronometric counting in this situation, thus eroding any possible psychological continuity between humans and animals. Likewise, large L/S ratios and small $L - S$ differences could be arranged only by using very short stimuli. Some evidence suggests that Weber's law may not be obeyed in such circumstances (e.g. Fetterman & Killeen, 1992), and so the data generated

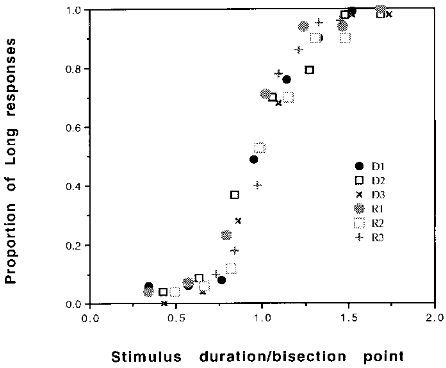

FIG. 2. Proportion of "long" responses from the different groups (D1, D2, D3, R1, R2, R3) plotted against stimulus duration expressed as a fraction of the bisection point for each group (MEAN in Table 2). Data points from the different groups are indicated by different characters in the figure, as shown in the key.

may not resemble those obtained from other studies of bisection where Weberian timing operates (e.g. Allan & Gibbon, 1991, and Figure 2 of this article).

In their studies of temporal bisection in humans, which invariably obtained geometric mean bisection, Allan and Gibbon (1991) also used small *L*/*S* ratios, with their *largest* value being 2:1. As mentioned above, there are many procedural differences between the studies of Allan and Gibbon (1991) and those conducted in our laboratory (reported in Wearden, 1991, and Wearden, & Ferrara, 1995). We used a larger subject population, and group mean data, whereas Allan and Gibbon used a much smaller subject population, but each subject received far more intensive training and testing than did ours, and individual subjects' data were presented. Furthermore, in Allan and Gibbon's study, subjects were presented with examples of the standard *S* and *L* and asked whether each presented stimulus *was* *S* or *L*, with occasional feedback being given. Our method in Experiment 1 above was very different, without explicit identification of *S* and *L* and without feedback. Nevertheless, in spite of all these differences, when we used an *L*/*S* ratio in the same range as that of Allan and Gibbon (1991) rather than the larger values we ordinarily use in our laboratories (up to 9:1, see Wearden, 1991, for example), we obtained the same result as they did, geometric mean bisection, whereas we replicated our previous results of near-arithmetic mean bisection at larger *L*/*S* values. This suggests that there is no real contradiction in the literature on temporal bisection in humans but, rather, an effect of stimulus range. Why such an effect might occur is considered further in the General Discussion.

EXPERIMENT 2

Experiment 1 provided support for the first part of Wearden and Ferrara's conjecture—namely, that geometric mean bisection might be obtained when *L*/*S* ratio was small but not when it was larger. The second part of their conjecture, that stimulus spacing effects (e.g. different effects of linear or logarithmic spacing of stimuli between *S* and *L*) can be obtained when *L*/*S* ratios are large but not when they are small was the focus of interest of Experiment 2. In this experiment, four groups of subjects were used. For two of these groups (LIN450 and LOG450), *S* was 450 msec and *L* was 900 msec, producing an *L*/*S* ratio of 2:1, as for group R3 of Experiment 1. Following on from the results of Experiment 1, we would anticipate near-geometric mean bisection in this case. In the LIN450 group, non-standard stimuli were spaced linearly between *S* and *L*; in the LOG450 group, the spacing of the stimuli between *S* and *L* was logarithmic. According to Wearden and Ferrara's conjecture, stimulus spacing effects should be small or absent in this case, because of the low *L*/*S* ratio.

For the other two groups (LIN50 and LOG50), *S* was 50 msec and *L* was 950 msec, a 19:1 *L*/*S* ratio—by far the largest used in any of our previous studies (Wearden 1991, 1993; Wearden & Ferrara, 1995). In this case we would expect marked stimulus spacing effects (the non-standard stimuli being linearly spaced in LIN50 and logarithmically spaced in LOG50) and a bisection point well above the geometric mean of *S* and *L*.

As mentioned above, Wearden and Ferrara (1995) used two different bisection methods, which they termed *similarity* and *partition*, although they found that the two methods produced very similar results when the same stimulus set was used. The partition method was used in the present Experiment 1; for Experiment 2, we reverted to the similarity method, which involves explicit identification of *S* and *L* (as in Wearden, 1991). The main aim of making this procedural change was to see whether geometric mean bisection at small *L/S* ratios would be obtained with the similarity method, which is procedurally much closer both to our original bisection study (Wearden, 1991), and also to the method used by Allan and Gibbon (1991) who used explicitly identified stimuli as *S* and *L*.

Method

Subjects

Eighty undergraduate students from the University of Liège, Belgium, participated for course credit. All were native French speakers or had near-native competence in French.

Apparatus

A PC8088 (IBM-compatible) computer controlled all experimental events. Apart from the different model of machine, all procedural details were as in Experiment 1.

Procedure

In the description given here, all relevant events are described as if they had been presented for English-speaking subjects, although in fact the use of the French language necessitated some differences (e.g. the keys used for the responses were L ("*long*") and C ("*court*"), not L and S, as described here). The general procedure was identical in all respects to that used in Wearden (1991), except that continuous tones served as stimuli to be timed. The subject pressed the spacebar of the computer keyboard to start the experiment, which commenced with 5 presentations of each of the standard short and long durations (*S* and *L*) identified by an appropriate display (e.g. *This is the standard short duration*). Stimulus presentations were separated by a 5-sec interpresentation interval. The subjects then received the display *Press spacebar for next trial*, and a press on the spacebar was followed by a delay that was randomly chosen from a uniform distribution running from 1 to 3 sec. A stimulus was then presented, and stimulus offset was followed by the display, *Was that more similar to the standard short stimulus (Press S), or the standard long (Press L)?*. The response was followed by a 3-sec delay, followed by the reappearance of the *Press spacebar for next trial* prompt. This procedure was repeated until all stimuli in a stimulus set (*S* and *L*, plus all the intermediate durations) had been presented once in a random order. Subjects then received two "refresher" presentations of *S* and *L*, conducted as at the start of the experiment, and this was followed by another series of stimulus durations to be classified as similar to *S* and *L*. The experiment continued until the stimulus had been presented 10 times—that is, the subject made 10 judgements about each stimulus in the stimulus set in the course of the experiment.

The stimulus sets used for the different groups of Experiment 2, with all values in msec, were:

LIN50: 50, 150, 250, 350, 450, 550, 650, 750, 850, 950
LOG50: 50, 69, 96, 133, 185, 256, 356, 493, 684, 950
LIN450: 450, 500, 550, 600, 650, 700, 750, 800, 850, 900
LOG450: 450, 486, 523, 567, 612, 658, 714, 771, 829, 900

Here, the first stimulus in the above lists served as *S*, the last as *L*.

Results and Discussion

Figure 3 shows the psychometric functions (mean proportion of "long" responses plotted against stimulus duration) for the LIN50 and LOG50 groups (left panel) and LIN450 and LOG450 groups (right panel). Data are shown by unconnected points (open circles for linear spacing conditions, filled circles for logarithmic spacing); the solid and dotted lines in each panel come from a theoretical model to be discussed later.

Inspection of the data in Figure 3 makes it immediately obvious that the effect of stimulus spacing (linear or logarithmic in the present case) was marked for stimuli intermediate between *S* and *L* when the *L*/*S* ratio was large (as in the LIN50 and LOG50 groups: left panel of Figure 3), but small or non-existent when the *L*/*S* ratio was small (LIN450 and LOG450 groups: right panel of Figure 3). The fact that the spacing of stimuli between *S* and *L* was different in the different conditions meant that the same intermediate stimuli did not occur in relevant comparison groups (e.g. LIN50 and LOG50), but the leftward shift of the psychophysical function can be tested by comparing the number of "long" responses at an intermediate stimulus from the LOG50 group with the number made to the stimulus from the LIN50 group with the next-longest duration. Thus we compared the following pairs of stimuli (first stimulus from the LOG50 group, second stimulus from LIN50 group): 185/250 msec, 256/350 msec, and 356/450 msec. Significantly more "long" responses occurred to the former stimulus than to the latter in the first and third cases, $t\,(38) = 2.122$ and 2.29, $p < 0.05$, respectively, and approached significance, $t = 2.002$, in the second. It should be noted that this comparison is an extremely conservative one, as it compares a stimulus duration from the LOG50 group with one from the LIN50 group, which can be nearly 100 msec longer. Similar comparisons between intermediate stimuli from the LIN450 and LOG450 groups never yielded statistical significance. Overall, therefore, this analysis

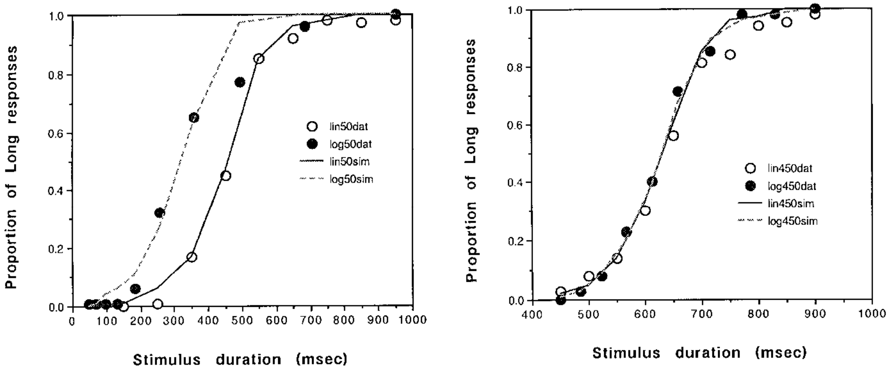

FIG. 3. Left panel: proportion of "long" responses plotted against stimulus duration for the LIN50 and LOG50 groups of Experiment 2 (lin50dat and log50dat); the solid and dashed lines connect points derived from the modified difference model (lin50sim and log50sim), with parameter values shown in Table 3. Right panel: data and simulated values from the LIN450 and LOG450 groups, with all details as in the left panel.

supports the impression gained from inspection of Figure 3 that stimulus spacing effects occur when the *L/S* ratio is large, but not when it is small.

As for the data in Experiment 1, bisection points for the four different stimulus sets of Experiment 2 were calculated according to three different methods (MINT, IINT, and REG—see description of Experiment 1, above), and results are shown in the lower part of Table 2. As in Experiment 1 and in Wearden and Ferrara (1995), all three methods for calculating the bisection point produced values within a few percentage points of each other, so these values are averaged to produce a MEAN in Table 2.

According to the results of Experiment 1, the bisection point should be above the geometric mean (and nearer to the arithmetic mean) of *S* and *L* when the *L/S* ratio is large (groups LIN50 and LOG50) but close to the geometric mean when the *L/S* is small (as in groups LIN450 and LOG450). The second prediction was certainly supported, as, in the LIN450 and LOG450 groups, the mean bisection point was almost identical to the geometric mean of *S* and *L*. In the LIN50 group, the bisection point greatly exceeded the geometric mean and was much closer to the arithmetic mean of *S* and *L*, although it was still some distance from it. The LOG50 group produced results that at first appear ambiguous, as the bisection point was very different from both the arithmetic and geometric means of *S* and *L* and lay between the two. The result may make more sense if we consider the mean of *all* the stimuli in the to-be-bisected set. When stimuli are spaced linearly between *S* and *L*, the arithmetic mean of *S* and *L* is also the arithmetic mean of the set, but this is not true when stimuli are logarithmically spaced between *S* and *L*. In the LIN50 group, the arithmetic mean of the entire set is 327 msec—a value much closer to the mean bisection point (295 msec) than either the arithmetic or geometric means of *S* and *L*. In their discussion of stimulus spacing effects in temporal bisection, Wearden and Ferrara (1995) explicitly assumed that subjects bisected stimulus sets by using the arithmetic mean of all the stimuli in the set, not just *S* and *L*. Their model, which reacted appropriately to changes in stimulus spacing even though it did not fit data perfectly in all respects, basically assumed that subjects responded "long" if they decided that some just-presented stimulus was discriminably longer than the mean and "short" if the stimulus was discriminably shorter, and they responded at random if the stimulus could not be discriminated from the mean. Stimulus spacing effects become less marked as the *S* to *L* stimulus range decreases, as the arithmetic mean of *S* and *L* becomes a better descriptor of the set mean in these cases (e.g. the difference between the mean of an arithmetically and logarithmically spaced set decreases as the ratio of *L* and *S* decreases).

Thus, overall, the data obtained in Experiment 2 verified the finding of near-geometric mean bisection when the *L/S* ratio is small and also illustrated that stimulus spacing effects are only clearly found when the *L/S* ratio is large (e.g. group LIN50 compared with LOG50) and are small or absent when the *L/S* ratio is small (e.g. group LIN450 compared with LOG450).

GENERAL DISCUSSION

The results of the two experiments above can be summarized with respect to two features of the bisection task: *bisection point location* and *stimulus spacing effects*.

Bisection Point Location. In data from both experiments, the bisection point was located close to the geometric mean of *S* and *L* (or even slightly below the geometric mean in some cases) when the *L/S* ratio was small, but closer to the arithmetic mean of *S* and *L* or the arithmetic mean of the stimulus set (e.g. the LOG50 group of Experiment 2) when the *L/S* ratio was larger. Although the line of division between "large" and "small" remains to be determined by more exhaustive parametric analyses, "small" seems to be 2:1 (and probably also less, see Allan & Gibbon, 1991), and "large" values greater than 2:1. Data from Experiment 1 also suggested that there was a small effect of *L* − *S* difference on the bisection point when *L/S* ratio was held constant at 4:1. As noted above, this result suggests that there is no important empirical contradiction between the data of the Wearden (1991) and Wearden and Ferrara (1995) studies, which found arithmetic mean bisection in humans (for another example, see Wearden, 1993), and the finding of geometric mean bisection by Allan and Gibbon (1991). In spite of the myriad procedural differences between the studies, when stimulus sets with "small" *L/S* ratios were used, geometric mean bisection was obtained with human subjects in all cases.

Stimulus Spacing Effects. The results of Experiment 2, above, taken together with those from Wearden and Ferrara (1995), strongly suggest that stimulus spacing effects on temporal bisection in humans are obtained only when the *L/S* ratio is "large" (i.e. greater than 2:1).

The finding of arithmetic mean bisection from humans when "large" *L/S* ratios are employed is supported by findings from a study that pre-dates recent interest in bisection and is rarely quoted in the English-speaking literature—that of Bovet (1968). Bovet employed tones with durations of $S = 0.3$ sec, $L = 1.65$ sec, and $S = 0.3$ sec and $L = 3.00$ sec. After hearing examples of these tones, subjects were required to produce a time interval (by button pressing:production method), or to adjust the length of a third tone (adjustment method), to result in a duration exactly half-way between the two standards. For the first case cited above (*L/S* ratio = 5.5), the average value obtained from subjects (0.91 sec from production, 0.90 sec from adjustment) was closer to the arithmetic mean of *S* and *L* (0.975 sec) than to the geometric mean (0.70 sec); for the second case (*L/S* ratio = 10), the results were even clearer (bisection point by production = 1.58 sec, by adjustment = 1.69 sec), with both values being much closer to the arithmetic mean (1.65 sec) than to the geometric mean (0.95 sec).

In the light of the finding that the location of the bisection point appears to depend on the *L/S* ratio in studies with humans, and to be close to the arithmetic mean when the *L/S* ratio is larger than about 2, we were prompted to attempt to characterize the location of the bisection point in animal studies when "large" *L/S* ratios were used.

The vast majority of studies of temporal bisection in animals have followed Church and Deluty's original article (1977) in using an *L/S* ratio of 4.0 or less, most commonly with S = 2 sec and *L* = 8 sec (e.g. see Maricq et al., 1981; Meck, 1983; Meck & Church, 1982; Roberts, 1982, for just some examples). In these cases, the bisection point was invariably located very close to the geometric mean of *S* and *L*, regardless of the absolute values of *S* and *L*.

A few experiments have used *L/S* ratios larger than 4.0, and some conditions of this type come from Platt and Davis (1983). These workers used a bisection technique that is somewhat different from that of Church and Deluty (1977) in that pigeons were reinforced, on each trial, for a response occurring on one of two keys in a pigeon chamber. On a random 50% of trials, the first response more than *S* sec after the start of the trial was reinforced on one key; on the other 50% the first response more than *L* sec after the start of the trial was reinforced on the other key. *L* was, by definition, greater than *S*, and the absolute values of *S* and *L*, as well as their ratio, were varied across conditions. The bisection point was calculated either from the crossover of the averaged response rate versus time functions on the two keys, or by a measure of switching between the keys. When the *L/S* ratio was less than 4.0, the geometric mean of *S* and *L* described the bisection point well, but at larger ratios (e.g. with $S = 10$ and $L = 160$ sec) the bisection point deviated from the geometric mean. However, the different methods of measuring the bisection point (from response rate or switching) disagreed as to the direction of the deviation (i.e. whether the bisection point was above or below the geometric mean). A major problem with studies of this type is that subjects may emit few or no responses for a period between *S* and *L* when the *L/S* ratio is large, rendering measurement of the bisection point impossible on most trials (Platt & Davis, 1983, p. 168).

An experiment with rats by Siegel (1986) used a method close to that of Church and Deluty (1977), with white noise signals of values $S = 1$ sec, $L = 16$ sec. The bisection point was located well *below* the geometric mean of *S* and *L* (e.g. at the geometric mean, 4 sec, 81.7% of responses were "long"). Unfortunately, the testing situation used "outside" signals (i.e. signals shorter than *S* or longer than *L*)—a manipulation that according to a second experiment reported by Siegel, made a difference to the location of the bisection point even when a "standard" 2/8 sec bisection condition was run. This, obviously, makes it difficult to interpret the results from the 16:1 *L/S* ratio used in the first experiment.

A number of studies by Raslear and colleagues have used rats in bisection studies with an *L/S* ratio greater than 4. For example, Shurtleff, Raslear, and Simmons (1990) used tones with $S = 0.5$ and $L = 5.0$ sec. For both the rats used in their Experiment 1, the bisection point was considerably above the geometric mean of *S* and *L* (1.58 sec), and nearer to the arithmetic mean (2.75 sec). In a similar study (Shurtleff, Raslear, Genovese, & Simmons, 1992) visual or auditory stimuli were used ($S = 0.5$, $L = 5.0$ sec), and the drugs physostigmine and scopolamine were administered in some conditions. When saline was administered as a control, the bisection point was invariably closer to the arithmetic mean than to the geometric mean, with results being particularly clear when tones were used as stimuli. Increasing doses of physostigmine had little effect on the bisection point, but increasing doses of scopolamine decreased the bisection point, which thus became closer to the geometric than arithmetic mean at larger doses. Overall, therefore, data from "normal" (i.e. undrugged) conditions of both studies resembled those obtained from humans in suggesting bisection points much closer to the arithmetic than geometric mean when a "large" *L/S* ratio, like 10:1, was used.

Finally, Raslear (1983) provided data on visual stimulus duration bisection in rats with a range of *L/S* ratios much greater than used in other studies—up to 100:1 (e.g. $S = 0.1$ sec, $L = 10$ sec). Unfortunately, the 8 individual rats used in the study did not all receive the same *S* and *L* values, nor the same intermediate stimulus lengths, rendering a simple summary of results from the multitude of different conditions very problematical.

For example, one problem is that some *L/S* ratios are unique to individual rats, so it is unclear how reliable results from these conditions are. In general, however, the bisection point was not always well described by the geometric mean of *S* and *L*, and deviations were usually in the direction of the bisection point being above the geometric mean (i.e. towards the arithmetic mean), although bisection points were sometimes well below the arithmetic mean.

Overall, therefore, this survey of animal experiments using *L/S* ratios greater than 4.0 suggests the rather negative conclusion that although geometric mean bisection appears to break down in these conditions, it is impossible, because of methodological problems with the various studies, to decide exactly where the bisection point does lie. Some studies suggest near-arithmetic mean bisection in these cases (e.g. Shurtleff et al., 1990, 1992), whereas others find bisection points below the geometric mean (e.g. Siegel, 1986), and others have results that are complex and difficult to interpret clearly (e.g. Platt & Davis, 1983; Raslear, 1983).

Modelling Stimulus Range Effects

Although results from experiments with animals regarding possible *L/S* range effects on bisection point location are ambiguous, our Experiments 1 and 2 above with humans found clear effects, so the obvious theoretical problem that arises is how to account for them. Some algebraic approaches to bisection (e.g. as discussed in Gibbon, 1981) simply use relations between values of *S*, *L*, and some just-presented stimulus, *t*, to derive bisection points, and thus cannot account either for stimulus spacing or stimulus range effects. One model that may have some promise, however, is the *modified difference model* used to fit bisection data in Wearden (1991).

The starting point of this model is the basic idea that subjects form memory representations of the "short" and "long" standards of the bisection task (*S* and *L*) and calculate the difference between each of these memory representations and the just-presented stimulus, *t*. The response in any particular case is (usually) based on which of these two differences is the smaller—that is, the model uses a similarity rule based on absolute difference. If *S* and *L* are represented on average accurately, and the just-presented stimulus is also timed accurately, then the differences $(t - S)$ and $(L - t)$ will be equal at the arithmetic mean of *S* and *L*. To account for deviations from arithmetic mean bisection, the modified difference model assumed further that when the two differences defined above were sufficiently similar (i.e. the difference between them was less than some threshold), the subject was biased to respond "long". Trial-to-trial variability in the model arose from the memory representations of *S* and *L*, which were represented as distributions with scalar properties—that is, distributions with accurate means (*S* and *L*) and with standard deviations that were proportional to these means.

Specifically, the model generated memory representations of *S* and *L* in the form of Gaussian distributions with means *S* and *L*, and some constant coefficient of variation (standard deviation/mean), *c*, thus yielding a standard deviation of *cS* for *S* and *cL* for *L*. On any particular trial, the model sampled from the distribution of *S* and *L*, to produce two values s^* and l^*, which varied from trial to trial by random sampling. The currently presented stimulus, *t*, was assumed to be timed without variance. The basis of behavioural output was the absolute difference between t and s^* and t and l^* [symbolized as $D(s^*, t)$ and $D(l^*, t)$]. If these differences were "similar" (i.e. expressed casually, the subject cannot tell whether t is closer to S or to L), then the model responded "long"; specifically, "long" responses occurred if the absolute difference between $D(s^*, t)$ and $D(l^*, t)$ was less than some threshold, x. If the differences were sufficiently different (i.e. greater than x), then the model used the smallest difference as the basis of output, by responding "short" when $D(s^*, t) < D(l^*, t)$ and "long" when $D(l^*, t) < D(s^*, t)$. The model thus has two parameters, c, the coefficient of variation of memory representations of S and L, and x, the difference threshold.

It is immediately obvious how this model might deal with stimulus range effects, as when the S to L range is small, a substantial proportion of intermediate stimuli might tend to be ambiguous (i.e. differences from S and L would be similar), and the model is biased towards responding "long" in these cases. When the stimulus range is larger, on the other hand, fewer intermediate stimuli are ambiguous, and on most trials the model uses the smallest difference to generate responding on most trials. Operating by itself, the difference rule will yield arithmetic mean bisection, as discussed above, but the "respond long" bias occurring under ambiguous conditions will tend to shift the psychophysical function to the left—that is, towards geometric mean bisection.

We applied this model to data from Experiments 1 and 2. Two questions arise: (1) Can parameter values be found that enable the model to fit data adequately in terms of goodness of fit (with a subsidiary question being whether the parameter values change coherently with changing conditions)? (2) With parameter values held constant, does the model behave appropriately as conditions are changed (e.g. with changes in the L/S ratio)?

The lines in the six panels of Figure 1 and the two of Figure 3 show the fits of the modified difference model to data, and Table 3 gives parameter values and mean absolute deviation (MAD) between data and the model's output (defined as the sum of the absolute deviation between data and fitted points, divided by the number of points). The fitted values were derived from simulation of 1000 trials at each stimulus duration modelled.

Inspection of Figures 1 and 3 and the MAD values shown in Table 3 indicates that the model fitted data well in most cases. The largest MAD value was 0.04, but in some cases most of the deviation arose from a single discrepant point. Overall, MAD values compare well with those obtained on other tasks, such as temporal generalization (Wearden, 1992; Wearden & Towse, 1994) and categorical timing (Wearden, 1995). Inspection of parameter values (c and x) reveals a less reassuring picture. In some cases, for example, threshold values were exceptionally low (0.01 for group R2 and even 0 for group D1), but in these instances the model fitted data where the bisection point exceeded the arithmetic mean, and thus the "long" response bias, which would have shifted the psychophysical function to the left and the bisection point below the arithmetic mean, was not needed. Another problematical case comes from the LOG50 group, where the very high difference threshold value (0.35) seems extremely implausible, as subjects can make much finer discriminations than this. However, data from this group also present a bisection point anomaly, as the location of this point was, uniquely in the data in Experiments 1 and 2, not well described by either the arithmetic or geometric mean of S and L, so the problems experienced by the modified difference model, which fits normal bisection data well, are perhaps unsurprising.

TABLE 3
Parameter Values for Fits
of the Modified Difference Model
to Data from Experiments 1 and 2

Group	*c*	*x*	*MAD*
D1	0.37	0	0.04
D2	0.31	0.06	0.03
D3	0.25	0.07	0.01
R1	0.26	0.04	0.01
R2	0.33	0.01	0.04
R3	0.18	0.08	0.03
LIN50	0.26	0.07	0.02
LOG50	0.27	0.35	0.04
LIN450	0.17	0.07	0.04
LOG450	0.17	0.07	0.02

Note: *c* is the coefficient of variation of representations of *S* and *L*; *x* is the difference threshold (see text for details); MAD is the mean absolute deviation between the data points and the predictions of the model: the total absolute deviation divided by the number of points fitted.

We next tested whether the modified difference model behaved appropriately when the stimulus range used in a bisection task was varied, with constant *c* and *x* values (0.2 and 0.1). We made no attempt to fit any particular data set, but instead simulated four different stimulus ranges. For all four, *L* was 900 msec and *S* varied over values of 100, 300, 450, and 600 msec. Stimuli were approximately linearly spaced between *S* and *L*, except that the geometric mean value was always included in the set so that the proportion of ‘‘long’’ responses occurring at this value could be measured. The stimulus ranges used (ranging from *L/S* ratios of 9:1 to 1.5:1) spanned most of the range used with humans, in experiments from Wearden (1991, 1993), Wearden and Ferrara (1995), the present study, and Allan and Gibbon (1991). One thousand trials at each stimulus value used were simulated, and the results are shown in Figure 4.

The left panel of Figure 4 shows the psychophysical functions produced in the four cases simulated. It is obvious that all exhibited the monotonically increasing proportion of ‘‘long’’ responses found in data when stimulus duration was increased, and that all functions had the approximately ogival shape found in data. The right panel abstracts from the overall results just the proportion of ‘‘long’’ responses occurring in the simulations at the arithmetic and geometric mean values, as the *L/S* ratio changed. It is clear from Figure 4 that the main effect of *L/S* ratio in the simulation is on the proportion of ‘‘long’’ responses occurring at the geometric mean. When the *L/S* ratio was 9:1, virtually no ‘‘long’’ responses were predicted at the geometric mean of *S* and *L*, and, in fact, very few are found in the data (Wearden, 1991). As the *L/S* ratio declined, however, an increasing proportion of ‘‘long’’ responses occurred at the geometric mean of *S* and *L*, with the 50% barrier being crossed somewhere between *L/S* ratios of 3:1 and 2:1. Of course, the *L/S* ratio that yields a bisection point at the geometric mean in the simula-

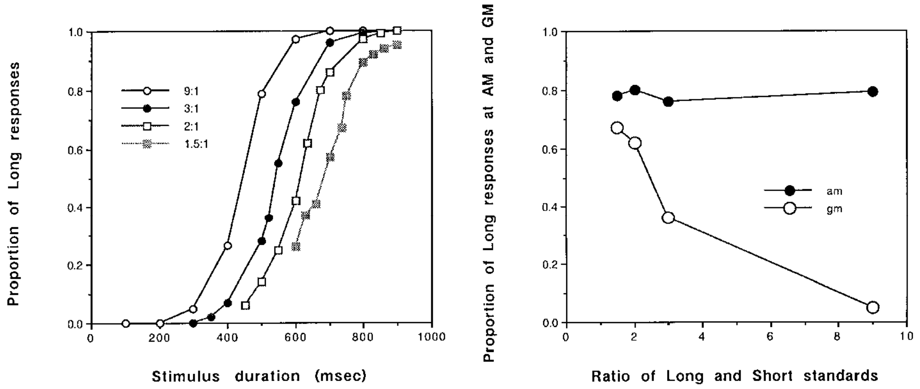

FIG. 4. Left panel: psychophysical functions produced by the simulations described in the text; in all cases L was 900 msec, and S varied from 100 to 600 msec, generating the 4 different L/S ratios indicated in the panel. Right panel: the proportion of "long" responses predicted by the simulation at the arithmetic mean of S and L (am: filled circles) and the geometric mean (gm: open circles) as the L/S ratio was changed.

tions depends upon the choice of parameters used, and the crossover from less than to greater than 50% "long" responses at the geometric mean will occur at different L/S values in other cases. In addition, the overall shape of the function relating the proportion of "long" responses at the geometric mean to the L/S ratio also depends on simulation parameter values, although the function will be continuous in all cases. In spite of these qualifications, the model accurately captured the increasing proportion of "long" responses occurring at the geometric mean as stimulus range decreases, with constant parameter values.

The principal fault of the modified difference model when applied to data from the present study is that it cannot simulate stimulus spacing effects when parameter values are kept constant. For example, for some constant c and x values, simulated data points from conditions used in the LIN50 and LOG50 groups of Experiment 2 superimpose, rather than exhibiting the leftward shift of the psychophysical function in the LOG50 group found in data (e.g. left panel of Figure 3). Although we do not present any results here, to save space, it is intuitively obvious that a model like the modified difference model has no mechanism for taking into account the context in which some stimulus duration, t, occurs, so for fixed S and L, a given value of t will always produce the same proportion of "long" responses. Wearden and Ferrara's model (from Wearden & Ferrara, 1995) can simulate stimulus spacing effects with reasonable accuracy but cannot deal with the stimulus range effects noted in data, above. Overall, therefore, it seems that neither model deals with all aspects of the data in a satisfactory way, although some parameter values can be found that will fit the modified difference model reasonably well to all the psychophysical functions obtained, as shown in Figures 1 and 3.

Whilst a coherent theoretical treatment of all the effects obtainable in temporal bisection with humans remains at present elusive (and we have explored some more complex models than that outlined above without obtaining an accord between data and theory that is better than the modified difference model provides), data in the present article strongly suggest that the literature on temporal bisection in humans is empirically consistent, with geometric mean bisection and absence of stimulus spacing effects occurring when the L/S ratio is low (see also Allan & Gibbon, 1991; Wearden & Ferrara, 1995) but with arithmetic mean bisection and marked spacing effects when the L/S ratio is larger. As these results seem reliable across studies conducted with different procedures and in different laboratories, they seem a reasonable basis for the development of some more coherent and comprehensive theory of bisection than exists at present.

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Effets de la marge de durée des stimuli dans la bisection temporelle chez le sujet humain

Deux expériences investiguent l'effet de la marge de stimuli sonores de courte durée sur la performance de bisection temporelle chez le sujet humain. Dans l'Expérience 1, six groupes de sujets son testés avec une tâche de bisection temporelle où chaque stimulus doit être classé comme "court" ou "long". Pour trois groupes, la différence entre les durées la plus longue (L) et la plus courte (S, Short) de l'ensemble des stimuli qui doit être bisecté reste constante à 400 ms., et le rapport L/S varie de 5:l à 2:1. Pour trois autres groupes, le rapport L/S est maintenu constant à 4:1 alors que la différence L–S varie de 300 à 600 ms. Le point de bisection (la valeur de stimulus produisant 50% de réponses "long") est plus proche de la moyenne arithmétique des stimuli L et S que de la moyenne géométrique chez tous les groupes, excepté celui dont le rapport L/S est 2:1 et pour lequel on obtient la bisection à la moyenne géométrique. Dans l'Expérience 2, l'espacement des stimuli entre L et S est linéaire ou logarithmique et le rapport L/S est 2:1 ou 19:1. Une bisection à la moyenne géométrique est obtenue dans les deux cas où le rapport L/S est 2:1, mais les effets de l'espacement des stimuli sont observés seulement lorsque le rapport L/S est 19:1. Globalement, les données vont dans le sens d'une supposition antérieure, selon laquelle le rapport L/S utilisé dans la tâche de bisection est un déterminant majeur de la performance. Un modèle théorique de la bisection proposé par Wearden (1991) rend adéquatement compte du déplacement des points de bisection discuté çidessus, mais est mis en difficultés par l'effet de l'espacement des stimuli.

Efectos del rango de estímulos sobre la bisección temporal en sujetos humanos

En dos experimentos con sujetos humanos, utilizando tonos de corta duración como estímulos, se estudió el efecto del rango del conjunto de estímulos sobre la actuación en una tarea de bisección temporal, en la que cada estímulo había de ser clasificado como "corto" o “largo”. En tres grupos de sujetos, la diferencia entre la duración más larga (L) y más corta (C) del conjunto de estímulos a biseccionar se mantuvo constante en 400 msegs., mientras que la razón C/L variaba entre 5:1 y 2:1. En otros tres grupos, la razón C/L se mantuvo constante, mientras que la diferencia L–C varió entre 300 y 600 msegs. El punto de bisección (valor de estímulo al que se daba un 50% de respuestas “largo”) se situó más cerca de la media artimética de C y L que de la media geométrica en todos los grupos, excepto an aquél para el que la razón C/L fue 2:1, en el que se observó bisección en función de la media geométrica. En el Experimento 2, los extímulos se espaciaron entre C y L según una escala lineal o según una escala logarítmica y el valor de la razón C/L fue de 2:1 o de 19:1. Se observó bisección geométrica en ambos casos cuando la razón C/L fue de 2:1, aunque sólo hubo efectos del espaciamiento de estímulos cuando la razón C/L fue de 19:1. En general, los resultados apoyan conjeturas anteriores sobre el papel determinante que la razón C/L desempeña en las tareas de bisección. Un modelo teórico propuesto por Wearden (1991) explica adecuadamente las desviaciones del punto de bisección observadas, aunque encuentra dificultades para explicar los efectos de espaciamiento.