Double bisection of auditory temporal intervals by humans

R. Emmanuel Trujano & Oscar Zamora

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ORIGINAL ARTICLE

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R. Emmanuel Trujano · Oscar Zamora

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Abstract Scalar Expectancy Theory (SET) has been the leading theory in timing research, and has also influenced research into human timing. However, other timing theories exist, such as Learning to Time (LeT). The double bisection task was designed to test the SET and LeT theories in pigeons. The purpose of this experiment was to verify whether similar results emerge from a human adaptation of the double bisection task. The results indicated that humans perform the double bisection task in the same way as pigeons do. However, the assumptions inherent in LeT cannot be applied to humans. Two other explanations are also assessed here.

Introduction

Since John Gibbon (1977, 1991) published the Scalar Expectancy Theory (SET) for the purpose of describing the temporal regularities in the behavior of organisms, many empirical findings have been unified within this theoretical framework (see Church, 2002 for a review). Even though other quantitative timing models exist (e.g., Killeen & Fetterman, 1988; Machado, 1997), SET has been the most influential research model to date.

One of the most commonly employed timing procedures is temporal bisection (Church & Deluty, 1977): animals are trained to emit a response R_1 to a short reference stimulus duration S and to emit a second response R_2 to a long reference stimulus duration L. When animals have learned to discriminate between S and L, intermediate durations t are introduced, where $S \leq t \leq L$. The animal's task is to categorize every intermediate duration t as either short or long. The usual results for this task when undertaken by nonhuman animals are: (1) the psychometric function which relates the proportion of LONG responses (p(LONG)) to stimulus duration grows monotonically as a sigmoidal shape, (2) the bisection point [the temporal duration at which $p(\text{LONG}) = 0.5$] is close to the geometric mean of the trained durations, (3) psychometric functions for all L/S ratios of trained durations superpose when normalized by their bisection points, (4) the Weber ratio (the difference limen divided by the bisection point) is constant for every L/S ratio and $L–S$ range (Church, 2002; Church & Deluty, 1977; see Gibbon, 1981, for a mathematical analysis).

In spite of the fact that Gibbon (1977, 1991) developed SET in order to describe nonhuman empirical findings, it has been successfully applied to human research (Allan, 1998; Malapani & Fairhurst, 2002; Wearden & Lejeune, 2008). Controlling for chronometric counting in humans by presenting stimulus durations in milliseconds ranges,[1] some of the results from the temporal bisection procedure for nonhuman animals have also been reported for humans (Allan, 2002a, 2002b; Allan & Gerhardt, 2001; Allan & Gibbon, 1991; Ortega & López, 2008; Wearden, 1991; Wearden & Bray, 2001; Wearden & Ferrara, 1995, 1996). A single exception exists which refers to the superposition of psychometric functions: although many studies have also reported adequate superposition (Allan, 1998, 2002a,

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[1] See for example Hinton and Rao (2004) for an empirical demonstration and Grondin (2001) for a theoretical treatment about the influence of chronometric counting on timing performance.

2002b; Allan & Gerhardt, 2001; Allan & Gibbon, 1991; Ortega & López, 2008; Wearden, 1991; Wearden & Bray, 2001; Wearden & Ferrara, 1995, 1996), contrary evidence can be found (Allan, 1998, Ortega, López, & Church, 2009, Penney, Allan, Meck, & Gibbon, 1998; see Wearden & Lejeune, 2008 for a discussion). Other discrepancies refer to the location of the bisection point: some studies have found that the bisection point is closer to the geometric mean (GM) of the reference durations (Allan, 2002b, exp. 3; Allan & Gibbon, 1991, Wearden & Ferrara, 1996, exp. 2), whereas others report that it is closer to the arithmetic mean (AM; Allan & Gerhardt, 2001; Wearden, 1991; Wearden & Ferrara, 1995, 1996). However, all of these results suggest that the bisection point is closer to AM when the *L/S* ratio of trained durations is elevated (for example, 5:1), and likewise it is closer to GM when the *L/S* ratio is 2:1 or less. Besides this, when the *L/S* ratio is elevated, two phenomena take place: (1) a spacing effect results (Wearden & Ferrara, 1995) so that a linear spacing of intermediate durations shifts the psychometric function to the right, in comparison to a psychometric function with a logarithmic spacing of intermediate durations, and (2) the Weber ratio increases (Ferrara, Lejeune, & Wearden, 1997), suggesting that timing sensitivity decreases.

If results in human timing research resemble those of animal research (see Malapani & Fairhurst, 2002 for a comparative review), then other timing procedures could be adapted to humans, like the double bisection task (Machado & Keen, 1999).

The double bisection task was employed by Machado and Keen (1999) in order to test the assumptions and predictions of two timing models: Gibbon's (1991) SET and Learning to Time (LeT; Machado, 1997). The structure of the task is as follows (see Fig. 1):

1. Pigeons perform a simple temporal bisection task (call it *Type 1*): they have to discriminate between a short stimulus duration S_1 and a long stimulus duration L_1 (the stimulus to be timed is commonly a white light). Once they have learned this, they have to categorize intermediate durations t. Usually, response options for S_1 and L_1 are associated with one key color each (for example red and green for S_1 and L_1 responses, respectively).
2. Following this, pigeons perform another simple bisection task (call it *Type 2*) similar to Type 1 bisection and with the same temporal marker (white light): they have to discriminate between a new short stimulus duration S_2 and a new long stimulus duration L_2. Once they have learned this, they have to categorize intermediate durations t. Response options for S_2 and L_2 are also associated with other key colors (such as blue and yellow for S_2 and L_2 responses, respectively). (Although *L*–*S* ranges are different for each bisection, *L/S* ratios are equal, and $L_1 = S_2$.)
3. Once pigeons perform adequately phases 1 and 2, a mixed bisection phase is presented in which trials from each bisection type are intermixed in the same session; each duration is presented with its respective associated response colors according to the bisection type where each one belongs.
4. Finally, in the double bisection phase per se, temporal durations between S_1 and L_2 are presented during the same session, and new combinations of key colors are presented for each duration.

Figure 2 presents the predictions of SET and LeT for the double bisection task. Consider SET first: it assumes that the animal forms a representation of the just recently experienced stimulus duration X_T and compares it against two samples, one coming from a distribution of remembered short durations X_S and another coming from a distribution of remembered long durations X_L: if the ratio X_S/X_T is greater than the ratio X_T/X_L then X_T is judged as more similar to X_S and the organism is more likely to respond *S*. This same process operates in both bisection types, and since the *L/S* ratios are equal, then SET predicts superposition of the two psychometric functions when the proportion of SHORT (red or blue) responses is plotted against relative stimulus durations (*t/S*; middle left panel) for both bisection types intermixed in the same session. Besides, since the organism compares ratios of estimated durations, the predicted bisection point equals $X_T = \sqrt{(X_S \times X_L)}$ that is, the geometric mean of *S* and *L* reference durations.

On the other hand, LeT assumes that a flow of serial behavioral states serves as a clue for choice response. The notion of behavioral states embodies the concepts of elicited, induced, interim, adjunctive and terminal behaviors, which refer to how some behaviors are most frequently displayed during some fraction of a temporal interval than others (see Fetterman, Killeen, & Hall, 1998; Staddon & Simmelhag, 1971). LeT proposes that after appearance of an event that predicts a significant biological event, a set of behavioral states is activated and the occurrence of an operant responses depends on the level of activation of the state and the strength of its association with the operant response. Response rate is determined by a multiplicative rule that combines the levels of activation and association. For instance, during bisection task only the earliest behavioral states are active at the beginning of the to-be-timed interval and, as time goes by, the activation spreads to the next states of the series. Choice depends on which behavioral states are the most active at the end of a stimulus: early states are the most active after a short duration, so they become coupled mainly with the *S* response due to reinforcement during training and less with the *L* response

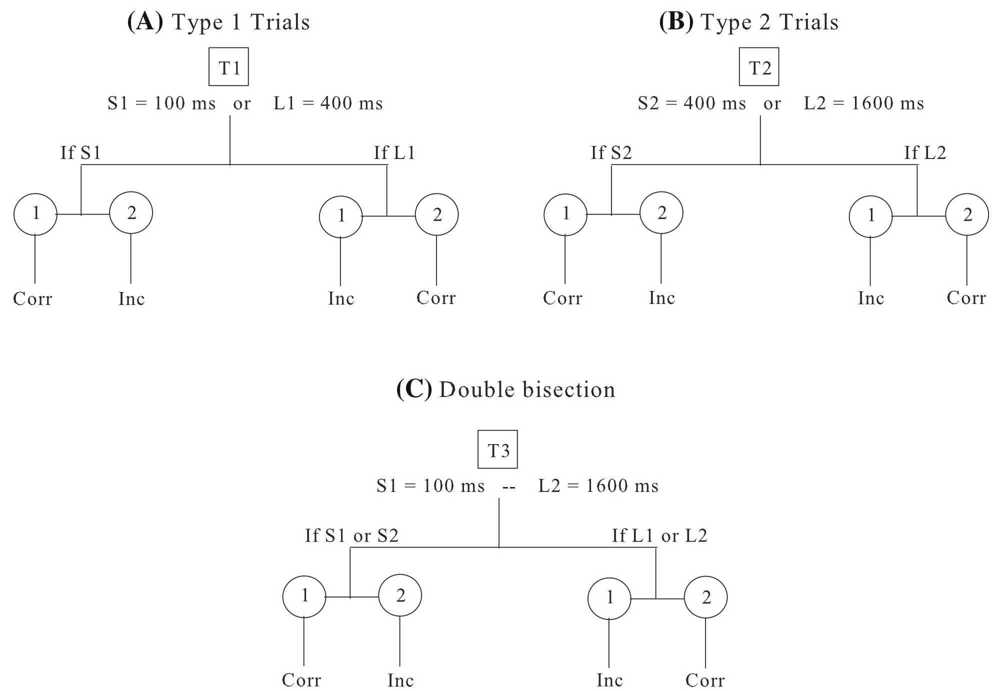

Fig. 1 General structure of the double bisection task. **a** *Phase 1: Type 1 simple bisection*. Reference durations $S_1 = 100$ ms and $L_1 = 400$ ms are trained by sounding one tone (T_1) and subsequently intermediate durations are presented. **b** *Phase 2: Type 2 simple bisection*. Reference durations $S_2 = 400$ ms and $L_2 = 1{,}600$ ms are trained by sounding a second tone (T_2) and then intermediate durations are presented for different sessions. Notice that $L_1 = S_2 = 400$ ms. **c** *Phase 4: double bisection*. Stimulus durations between S_1 and L_2 are defined by sounding a third tone (T_3). See "Procedure" for details

due to nonreinforcement; conversely, later states are the most active after a long duration, so they become coupled mainly with the *L* response due to reinforcement during training and less with the *S* response due to nonreinforcement. According to LeT, subjects learn by reinforcement to approach S_1 when signal duration is 1 s and to avoid L_1 by extinction, but they also learn to approach L_1 when signal duration is 4 s and to avoid S_1 by extinction. Conversely, they simultaneously learn by reinforcement to approach L_2 when signal duration is 16 s and to avoid S_2 by extinction, and they also learn to approach S_2 when signal duration is 4 s and to avoid L_2 by extinction. Since LeT assumes that the spread of activation across the behavioral states is proportional to the overall reinforcement rate, it predicts lack of superposition of the psychometric functions of mixed bisections, that is, the psychometric function for the Type 2 bisection should be steeper than that for the Type 1 bisection because the overall reinforcement rate remains constant (middle right panel). Furthermore, it predicts the bisection points to be higher than the geometric mean of *S* and *L* reference durations.

The critical test between SET and LeT according to Machado, Malheiro and Erlhagen (2009) is the proportion of L_1 responses as a function of stimulus duration in the double bisection phase per se (bottom panels), that is, the proportion of L_1 responses when trials include choice between L_1 (green) and S_2 (blue) options. Notice that L_1 and S_2 are associated with the same stimulus duration: 4 s; therefore, SET predicts indifference to any stimulus duration (lower left panel) because the organism compares every duration against samples from two identical distributions of remembered durations, whereas LeT predicts a monotonic growing preference for L_1 as stimulus duration increases (lower right panel) because the middle behavioral states are equally associated to both options, but early behavioral states in the series are less associated to L_1 for brief durations so that preference for L_1 is low, and latter behavioral states in the series are most associated to L_1 for longer durations so that preference for L_1 increases as stimulus durations increase. (See Machado & Pata, 2005, for a mathematical derivation of the theoretical curves deployed in Fig. 2.)

All results reported using this procedure coincide in terms of support of LeT's predictions (Arantes, 2008; Arantes & Machado, 2008; Machado & Arantes, 2006; Machado & Keen, 1999; Machado & Pata, 2005; Maia & Machado, 2009; Oliveira & Machado, 2008, 2009): the psychometric functions relating the proportion of SHORT responses to stimulus duration for the two bisection types do not always superpose when plotted against *t/S*, even though the *L/S* ratios are equal for both bisection types. Instead, the functions with the largest *S* and *L* values have a

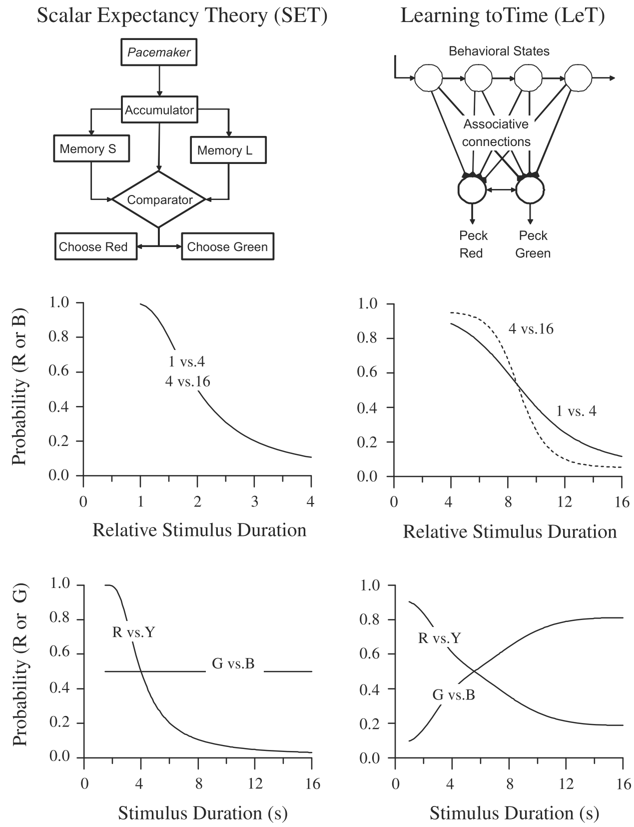

Fig. 2 Predicted results for the double bisection task made by two timing theories: Scalar Expectancy Theory (SET, *left panels*) and Learning to Time (LeT, *right panels*). *Top panels* general structure of both theories. *Middle panels* predicted results for the mixed bisections phase. SET predicts superposition of both psychometric functions when relative stimulus durations are plotted, whereas LeT predicts a steeper slope for the Type 2 bisection. *Bottom panels* predicted results for the double bisection phase. On the critical test, in which L_1 (*green*) and S_2 (*blue*) options are presented, SET predicts indifference to any stimulus duration, whereas LeT predicts a growing preference for the green option as stimulus duration increases. (Reprinted from Oliveira and Machado 2008, pp. 74, with permission from Elsevier.)

steeper slope. (Although not analyzed in any report, this contradicts Weber's law.) Besides, the bisection point is not close to the geometric mean of *S* and *L* reference durations, rather its value is higher than this, as predicted by LeT (see Machado, 1997). Finally, the proportion of LONG (green) responses grows as stimulus duration increases in the double bisection phase.

If nonhuman animals are able to process two or more temporal intervals simultaneously (Church, Guilhardi, Keen, MacInnis, & Kirkpatrick, 2003) and similar results have been reported for humans (Allan, 2002a; Allan & Gerhardt, 2001; Wearden & Bray, 2001), then it is possible to adapt the double bisection procedure for humans. The purpose of this experiment is to verify whether similar results can be found in a double bisection task adapted for humans. This adaptation, however, is not an exact replica of the original procedure in pigeons because it has been shown that temporal discrimination in humans gets compromised when the same temporal marker is employed to train two or more different duration ranges (Grondin, 2005; Grondin, Gamache, Roussel, Pouliot, & Plourde, 2005); instead, different temporal markers were employed to train the two bisection types of the original double bisection task. After a group of human participants performed this adapted double bisection task, psychometric functions relating the proportion of SHORT responses to stimulus durations for the first three phases were analyzed. In the last phase, psychometric functions relating the proportion of LONG responses to stimulus durations were analyzed. Besides this, bisection points, difference limens and Weber ratios for all experimental phases were analyzed.

Method

Participants

Forty-two undergraduate psychology students from the National Autonomous University of México participated in the experiment (36 women and 6 men; mean age = 20.24 years, SD = 1.86). All participants were randomly allocated to one of two equal-sized groups (see "Procedure" for details): linear (LIN; $n = 21$) and logarithmic (LOG; $n = 21$). All students gave their informed consent and participated in order to gain extra course credits. The whole experiment was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Apparatus

Participants were tested in groups of six per session in a quiet room. For every participant, a Dell Dimension DM051 computer with a SVGA monitor screen controlled the experimental task and recorded data with SuperLab Pro 4.0 for Windows (Cedrus Corporation). Two alphanumeric keys (1 and 2) from the keyboard were selected as response keys. The stimulus consisted of three tones (500, 1,000 and 1,500 Hz), transmitted through earphones. Every bisection type was presented with only one of the three tones, and tones relating to each experimental phase were counterbalanced across all participants.

Procedure

As mentioned above, SET and LeT predict different locations of the bisection points: SET predicts that they equal the geometric mean of *S* and *L* reference duration, whereas LeT predicts them to be higher than the geometric mean.

Since stimulus spacing shifts the psychometric function to either side, which in turn could bias the location of the bisection point either toward the geometric mean of S and L or away from it, participants were divided into two groups according to stimulus duration spacing: for one of the groups, linear spacing was presented (LIN group); for the other group, logarithmic spacing was presented (LOG group). Figure 1 presents the general structure of the experiment: every bisection type diagramed in Fig. 1 was trained with a different tone so that latter on the experiment the tone defined which stimulus duration belonged to which bisection type. It was divided into phases as follows:

Phase 1: Type 1 simple bisection (*100–400 ms*) Figure 1a shows the structure of this phase: the participant had to press a key in order to initiate each trial. The training block consisted of five alternating presentations (SLSLSLSLSL) of each of two reference durations: a short stimulus duration S_1 100 ms in time span and a long stimulus duration L_1 400 ms in time span. Instructions displayed on the screen to the participants were as follows:

Coming up you are going to be presented with a tone of two durations: a short duration and a long duration. Pay attention to them. Press the "1" key when you are ready to start.

All the referents were identified before presentation by a 2,500 ms display ("THIS IS A SHORT STIMULUS" for S_1, and "THIS IS A LONG STIMULUS" for L_1), and participants were instructed only to attend to these. After each presentation, an inter-trial interval (ITI) which represented a randomly chosen value from a uniform distribution ranging from 1,000 to 3,000 ms was presented.

After training, a generalization block was presented. Five intermediate durations t were introduced along with the reference durations. Instructions displayed on the screen to the participants were as follows:

Coming up you are going to be presented with a series of tones of different durations. Your task will be to say which duration was each: if it is a short duration press the "1" key, if it is a long duration press the "2" key. Press the "1" key when you are ready to start.

The structure of a generalization trial was as follows: the participant must press a key in order to initiate each trial, a 750 ms inter-stimulus interval (ISI) was presented and immediately after this, one of the seven stimulus duration started. At the end a 750 ms delay was presented and subsequently, the participant was asked to judge whether the stimulus duration was short or long by pressing the appropriate key, and no feedback was presented for any response. Once the participant had responded, an ITI value was randomly chosen and presented out of a uniform distribution ranging from 1,000 to 3,000 ms, and then the next trial began. For each group, the employed durations of the stimulus (in ms) were:

$$\text{LIN100} : 100, 150, 200, 250, 300, 350, 400$$
$$\text{LOG100} : 100, 125, 159, 200, 252, 317, 400$$

Each duration was presented 10 times, for a total of 70 generalization trials and all were randomly presented. After participants had completed this phase, they were permitted a time out. During this phase, the temporal marker was a filled auditory interval defined by sounding one of the three tones (e.g., 500 Hz).

Phase 2: Type 2 simple bisection (*400–1,600 ms*) Figure 1b illustrates the structure of this phase: this was similar to phase 1 except for the following factors: (1) the two reference durations were a new short stimulus duration S_2 400 ms long, and a new long stimulus duration L_2 1,600 ms long; (2) for every group, the stimulus durations (in ms) presented in the generalization block were:

$$\text{LIN400} : 400, 600, 800, 1{,}000, 1,200, 1,400, 1,600$$
$$\text{LOG400} : 400, 504, 635, 800, 1{,}008, 1,269, 1,600;$$

(3) the temporal marker was a filled auditory interval defined by sounding one of the three tones, but different from the one used in phase 1 (e.g., 1,000 Hz).

Each duration was also presented 10 times, for a total of 70 generalization trials presented randomly. (Notice that, although L–S ranges are different between the two bisection types, L/S ratios are equal—4:1—and $L_1 = S_2 =$ 400 ms.) Instructions provided to participants were the same as those for phase 1. Once the participants completed this phase, they were permitted another time out.

Half the participants were first presented with Type 1 simple bisection; whereas the other half were first presented with Type 2 simple bisection.

Phase 3: Mixed bisections (*Type 1 and 2 simultaneously*) In this phase, the whole 14 stimulus durations from both bisection types (seven generalization durations each) were presented within the same block for the two groups. Each duration was defined by the tone that was initially sounded, for each bisection type. For example, if Type 1 simple bisection was sounded by a 500 Hz tone and Type 2 simple bisection was sounded by a 1,500 Hz tone, this same assignment was used when both types were presented within the same block. Instructions displayed on the screen to the participants were as follows:

Coming up you are going to be presented with other durations. Your task will still be to say which duration was each: if it is a short duration press the "1" key, if it is a long duration press the "2" key. Press the "1" key when you are ready to start.

From Type 1 bisection, each of its seven durations was presented 6 times, totaling 42 trials. Likewise from Type 2 bisection, each of its seven durations was also presented 6 times for a total of 42 trials. A total of 84 trials were randomly presented in this phase. When the participants completed this phase, they were granted another time out.

Phase 4: Double bisection Figure 1c illustrates the structure of this phase: all stimulus durations from both bisection types were presented within the same block for the two groups with a new temporal marker which was different from those employed in previous phases. Specifically, the temporal marker for all stimulus durations was a filled auditory interval, which was sounded by one of the three tones, but a different one from those used in phase 1 to 3 (e.g., 1,500 Hz). Note that this third tone had never been sounded before. Instructions provided to participants were the same as those for phase 3. All durations from the Type 1 bisection were presented 6 times each, for a total of 42 trials; and those from the Type 2 bisection were also presented 6 times each, for a total of 42 trials. A total of 84 trials were randomly presented in this phase. (Also note that the 400 ms duration was presented 12 times; this was done in order to maintain the number of trials constant across phases 3 and 4.)

All experimental phases were presented within one session, lasting 45 min.

Data analysis

For each participant, a psychometric function which related the proportion of SHORT responses to stimulus duration was obtained from phases 1 and 2. For phase 3, two of these psychometric functions relating the proportion of SHORT responses to stimulus duration were also obtained, one for each bisection type. For phase 4, the obtained psychometric function related the proportion of LONG responses to stimulus duration; this is because, as Fig. 2 suggests, the critical results have been obtained as a proportion of LONG responses. Now, since the relative scales of the psychometric functions are different in the case of bisection in humans than in the case of double bisection in pigeons, they were obtained in two ways that will be called *superposition methods* for all psychometric functions: (1) a relative duration obtained by dividing all stimulus durations by the shortest duration in every bisection type; (2) a relative duration obtained by dividing all stimulus durations with the corresponding bisection point for each bisection type. (The former is common practice in double bisection tasks, but Penney et al., 1998 argue that the latter should turn in complete superposition when employed no matter the *L/S* ratio and *L–S* range employed. Therefore, the latter method is a better superposition test the than the proposed in the double bisection experiments.)

In order to compare the psychometric functions from each of the phases, a three-parameter sigmoidal function was fitted to individual psychometric functions:

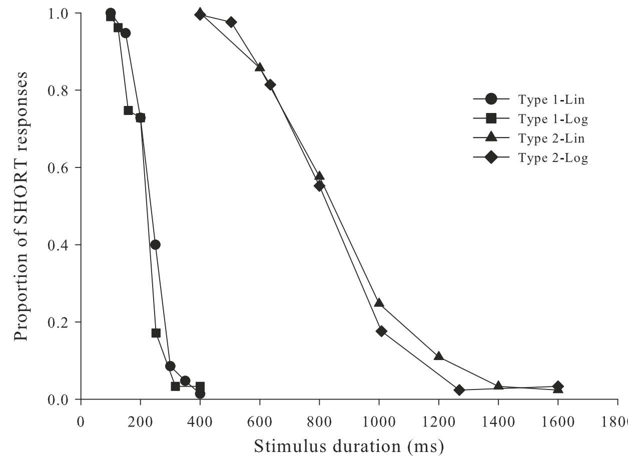

Fig. 3 Mean proportion of SHORT responses as a function of stimulus duration for Type 1 (S_1 = 100 ms vs. L_1 = 400 ms) and Type 2 (S_2 = 400 ms vs. L_2 = 1,600 ms) simple bisections and for the two spacing groups

$$p(Y) = \frac{a}{1 + e^{\left(\frac{-t - x_0}{b}\right)}} \quad (1)$$

where t is the stimulus duration, a is the maximum value of the function, x_0 is the stimulus duration at which the sigmoid has raised half of its height, and b is the slope parameter.

Once parameters had been calculated, the bisection point (the temporal duration at which $p(\text{SHORT}) = 0.5$), difference limen (half the difference between the time at which $p(\text{SHORT}) = 0.25$ and the time at which $p(\text{SHORT}) = 0.75$) and Weber ratio (difference limen divided by bisection point) were calculated. Comparisons were made between LIN and LOG groups and between the different experimental phases.

Results

Simple temporal bisections

Figure 3 shows the mean proportion of SHORT responses as a function of stimulus duration for Type 1 and Type 2 simple bisections and for the two spacing groups. As can be seen, the proportion of SHORT responses decays monotonically as stimulus duration increases.

Visual evidence suggests that the psychometric functions are very similar between LIN and LOG groups. To further evaluate whether there were differences in the psychometric functions between stimulus spacing groups, bisection points, difference limen and Weber ratios were compared (see Table 1). It is apparent in Table 1 that the LIN group tended to have higher bisection points and higher difference limens in the case of both simple bisection types. However, a t test for independent groups

Table 1 Mean (and standard deviations) bisection points (in ms), difference limen and Weber ratios for each spacing group in Type 1 and Type 2 simple bisections

Parameters	Bisection type	Spacing group	
		LIN	LOG
Bisection point	Type 1 (100–400)	229.84 (36.47)	209.65 (41.56)
	Type 2 (400–1,600)	816.91 (206.05)	798.69 (131.38)
Difference limen	Type 1 (100–400)	26.08 (15.13)	22.19 (21.95)
	Type 2 (400–1,600)	101.90 (57.47)	90.85 (54.35)
Weber ratio	Type 1 (100–400)	0.12 (0.07)	0.13 (0.13)
	Type 2 (400–1,600)	0.13 (0.09)	0.12 (0.08)

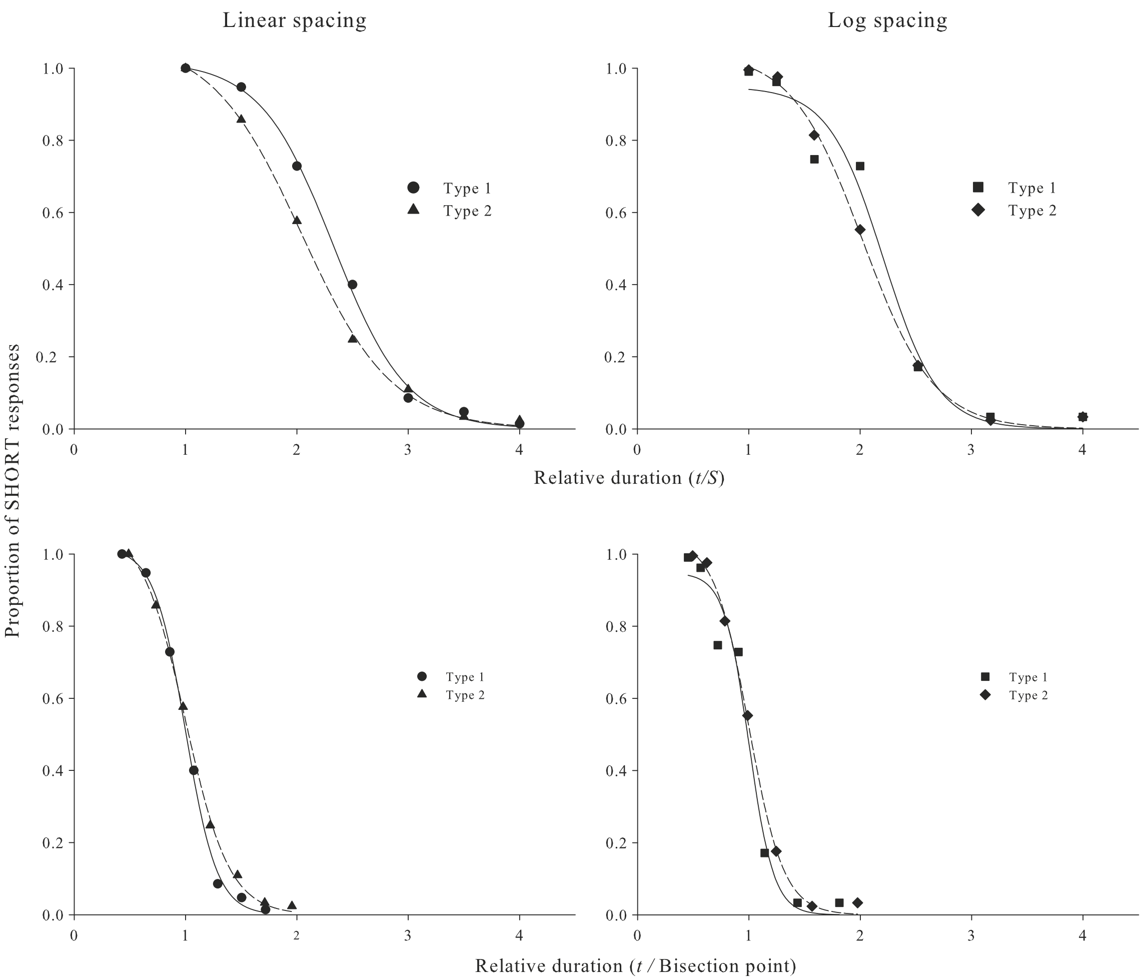

Fig. 4 Mean proportion of SHORT responses plotted against relative stimulus duration for phases 1 and 2 and for both LIN spacing (*left*) and LOG spacing (*right*) groups. *Top panels* relative stimulus duration calculated by dividing each duration by the shortest duration. *Bottom panels* relative stimulus duration calculated by dividing each duration by the bisection point. *Continuous* and *dashed lines* correspond to the best-fitting sigmoidal function for Type 1 and Type 2 bisections, respectively, drawn from Eq. 1

revealed no statistically significant differences between groups, either in terms of the bisection points (for Type 1 bisection, $t_{(40)} = 1.67$, $p > 0.05$; for Type 2 bisection,[2] $t_{(40)} = 0.05$, $p > 0.05$) or concerning the difference limen (For Type 1 bisection, $t_{(40)} = 0.67$, $p > 0.05$; for Type 2 bisection, $t_{(40)} = 0.64$, $p > 0.05$).

To test the scalar property, the four psychometric functions were superposed (see Fig. 4). For every bisection type and for every stimulus spacing group, all stimulus durations were divided by the shortest duration in every

[2] A log transformation was performed in order to correct the heteroscedasticity of the bisection point distribution in Type 2 bisection.

bisection type (upper panels of Fig. 4) and by their corresponding bisection point (lower panels of Fig. 4). Also shown are the best-fitting sigmoidal functions drawn from Eq. 1 for Type 1 (continuous lines) and Type 2 (dashed lines) bisections. As Fig. 4 shows, the psychometric functions superpose better when normalized by the bisection point. Nevertheless, a 2 × 2 mixed ANOVA performed on Weber ratios, with stimulus spacing as between-subjects factor and bisection type as within-subjects factor, yielded neither an effect of spacing ($F_{(1,40)} = 0.04$, $p > 0.05$), nor bisection type ($F_{(1,40)} = 0.09$, $p > 0.05$), nor an interaction effect ($F_{(1,40)} = 0.37$, $p > 0.05$).

Mixed temporal bisections

Not all the participants performed the mixed bisections accurately: some of them emitted either exclusively SHORT or exclusively LONG responses to all durations within a bisection type, and some responded in a manner that did not allow to calculate a difference limen [that is, the times at which p(SHORT) = 0.25 and 0.75 did not exist]. So, data from those participants were separated for further analysis, leaving analyzable data sets from only 24 out of 42 participants for Type 1 mixed bisection, and 28 out of 42 participants for Type 2 mixed bisection. Figure 5 shows the mean proportion of SHORT responses as a function of stimulus duration for the two spacing groups and for Type 1 and Type 2 temporal bisections presented in an intermixed fashion. It should be noted that the only difference between the first three experimental phases concerns the way that temporal bisection types were presented: in phases 1 and 2, the two temporal bisection types were presented alone, and in phase 3 they were presented within the same block. But since the stimulus durations and the tasks were the same for the different phases, neither the psychometric functions nor their parameters should have been different.

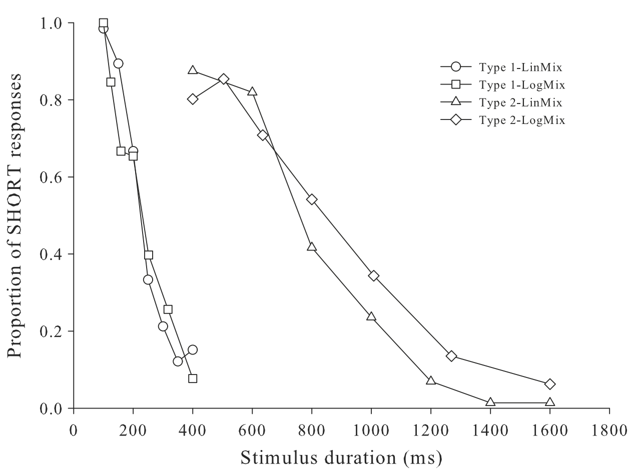

Fig. 5 Mean proportion of SHORT responses as a function of stimulus duration for Type 1 ($S_1 = 100$ ms vs. $L_1 = 400$ ms) and Type 2 ($S_2 = 400$ ms vs. $L_2 = 1{,}600$ ms) bisections and for the two spacing groups when presented intermixed

The shape of the psychometric functions in Fig. 5 suggests that duration discrimination accuracy diminished in mixed bisections when compared with bisections presented alone. This is indicated by the facts that: (1) Type 1 mixed bisection did not decrease to as low as zero, and (2) Type 2 mixed bisection did not decrease from 1.0, that is, the proportion of SHORT responses did not reach 1.0 for the shortest duration. In order to test them, t tests for single means were conducted on the mean proportion of SHORT responses for the long reference duration of Type 1 bisection ($L_1 = 400$ ms) and for the short reference duration of Type 2 bisection ($S_2 = 400$ ms) in both spacing groups. Table 2 shows the results along with the value against each mean was compared: t tests revealed that Type 1 mixed bisection did not decrease toward zero but Type 1 bisection alone did. Conversely, Type 2 mixed bisection did not reach 1.0 but Type 2 bisection alone did. (Furthermore, all participants in the LIN group responded "SHORT" to every single presentation of the shortest duration of Type 2 bisection alone, so no variance can be calculated and, therefore, neither can a t value.)

To further evaluate whether there were differences in terms of the psychometric functions between stimulus spacing groups and between phases 1 and 3 (Type 1 bisection presented alone and intermixed, respectively) bisection points, difference limen and Weber ratios from the 24 remaining participants for this bisection type were compared (see Table 3).

A 2 × 2 mixed ANOVA performed on bisection points, with stimulus spacing as between-subjects factor and phase as within-subjects factor, yielded neither effect of spacing ($F_{(1,22)} = 0.24$, $p > 0.05$), nor of phase ($F_{(1,22)} = 1.69$, $p > 0.05$), nor an interaction effect ($F_{(1,22)} = 1.41$, $p > 0.05$).

To test the participant's sensitivity to temporal durations between phases, a 2 × 2 mixed ANOVA referring to the difference limen, with stimulus spacing as between-subjects factor and the phase as within-subjects factor, yielded a significant effect of phase ($F_{(1,22)} = 8.52$, $p < 0.05$), but not of spacing ($F_{(1,22)} = 0.85$, $p > 0.05$), nor an interaction effect ($F_{(1,22)} = 1.41$, $p > 0.05$). Besides this, another 2 × 2 mixed ANOVA, with the same predictors, was applied to the Weber ratios, revealing a phase effect ($F_{(1,22)} = 8.89$, $p < 0.05$), but not a spacing one ($F_{(1,22)} = 0.12$, $p > 0.05$), nor an interaction effect ($F_{(1,22)} = 0.09$, $p > 0.05$).

These same analyses were conducted on the psychometric functions between stimulus spacing groups and between phases 2 and 3 (Type 2 bisection presented alone and intermixed, respectively; see Table 4). Once again, only data from the 28 remaining participants for this bisection type were analyzed. A 2 × 2 mixed ANOVA

Table 2 Statistics of the proportion of SHORT responses for the long and short reference duration of Type 1 and Type 2 bisections (respectively) and for both spacing groups

Spacing group	Bisection type	Stimulus duration (ms)	Mean *p*(SHORT)	Reference to compare[a]	*t*	*df*	*p*
Linear	Type 1	400 (L_1)	0.01 (0.03)	0	1.00	10	0.34
	Type 1 (Mix)	400 (L_1)	0.15 (0.12)	0	4.30	10	<0.05
	Type 2	400 (S_2)	1.00 (0.00)	1	–	11	–
	Type 2 (Mix)	400 (S_2)	0.88 (0.14)	1	−3.00	11	<0.05
Logarithmic	Type 1	400 (L_1)	0.02 (0.04)	0	1.90	12	0.08
	Type 1 (Mix)	400 (L_1)	0.08 (0.11)	0	2.52	12	<0.05
	Type 2	400 (S_2)	0.99 (0.02)	1	−1.00	16	0.33
	Type 2 (Mix)	400 (S_2)	0.81 (0.16)	1	−4.97	16	<0.05

[a] Values against each mean was compared

Table 3 Mean (and standard deviations) bisection points (in ms), difference limen and Weber ratio for each spacing group in Type 1 simple bisections, alone and intermixed

Parameters	Bisection type	Spacing group	
		LIN	LOG
Bisection point	Type 1	217.81 (43.44)	198.44 (45.72)
	Type 1 (Mix)	219.49 (38.92)	220.82 (67.72)
Difference limen	Type 1	25.51 (12.31)	21.94 (16.14)
	Type 1 (Mix)	42.06 (23.65)	62.76 (57.46)
Weber ratio	Type 1	0.12 (0.07)	0.13 (0.11)
	Type 1 (Mix)	0.20 (0.11)	0.26 (0.18)

Table 4 Mean (and standard deviations) bisection points (in ms), difference limen and Weber ratio for each spacing group in Type 2 simple bisections, alone and intermixed

Parameters	Bisection type	Spacing group	
		LIN	LOG
Bisection point	Type 2	834.84 (186.65)	843.50 (118.03)
	Type 2 (Mix)	804.45 (203.69)	875.11 (242.75)
Difference limen	Type 2	107.57 (53.39)	96.20 (55.05)
	Type 2 (Mix)	81.42 (76.13)	126.18 (95.54)
Weber ratio	Type 2	0.14 (0.08)	0.12 (0.08)
	Type 2 (Mix)	0.10 (0.10)	0.15 (0.11)

conducted on the bisection points, with stimulus spacing as between-subjects factor and phase as within-subjects factor, did not reveal, either effects of phase ($F_{(1,26)} = 0.02$, $p > 0.05$), or of spacing ($F_{(1,26)} = 0.38$, $p > 0.05$), or an interaction effect ($F_{(1,26)} = 0.74$, $p > 0.05$).

The same 2 × 2 mixed ANOVA conducted on the difference limens did not reveal either effects of phase ($F_{(1,26)} = 0.08$, $p > 0.05$), nor of spacing ($F_{(1,26)} = 0.36$, $p > 0.05$), nor an interaction effect ($F_{(1,26)} = 1.77, p > 0.05$). Finally, the same 2 × 2 mixed ANOVA conducted on the Weber ratios did not reveal either effects of phase ($F_{(1,26)} = 0.001$, $p > 0.05$), or of spacing ($F_{(1,26)} = 0.34$, $p > 0.05$), or an interaction effect ($F_{(1,26)} = 1.27, p > 0.05$).

To test the scalar property, the four psychometric functions in Fig. 5 were superposed (see Fig. 6). The same superposition methods employed in Fig. 4 were employed once again. Evidently, there is no superposition for either of the two methods. Instead, the Type 1 bisection functions indicate that this type generated more SHORT responses than Type 2 when both were intermixed; this is shown by the Type 1 functions being over the Type 2 functions.

Now, the left panel of Fig. 7 shows the mean proportion of SHORT responses plotted against stimulus duration for those participants who did not perform the mixed bisections accurately. Notice that this kind of performance prevents from calculating any index because the definition of the bisection point cannot be accomplished and, as a consequence, no Weber ratio can be calculated either (see "Data analysis"). Instead, it seems that participants integrated both bisections as a single one, that is, they

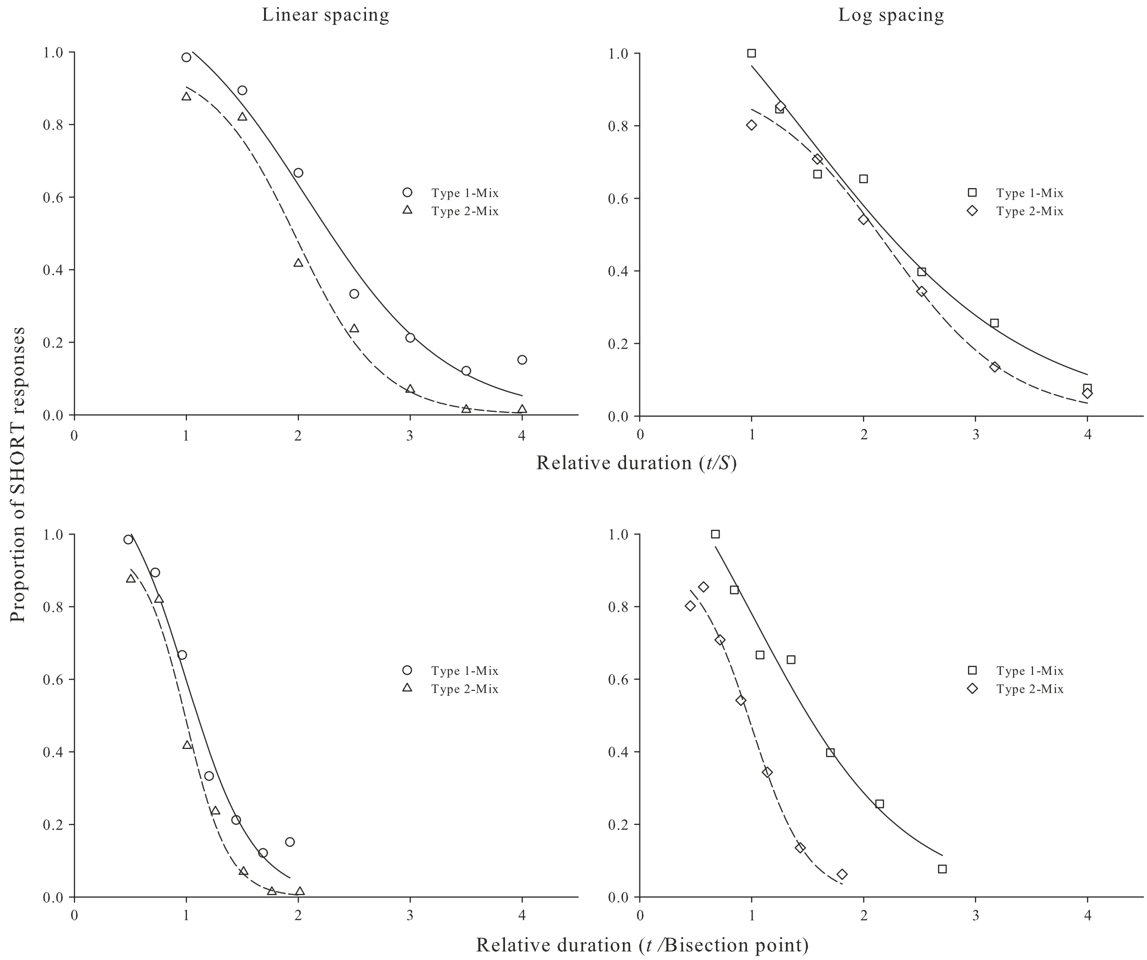

Fig. 6 Mean proportion of SHORT responses plotted against relative stimulus duration for mixed bisections and for both spacing groups. *Top panels* relative stimulus duration calculated by dividing each duration by the shortest duration. *Bottom panels* relative stimulus duration calculated by dividing each duration by the bisection point. *Continuous* and *dashed lines* correspond to the best-fitting sigmoidal function for Type 1 and Type 2 bisections respectively, drawn from Eq. 1

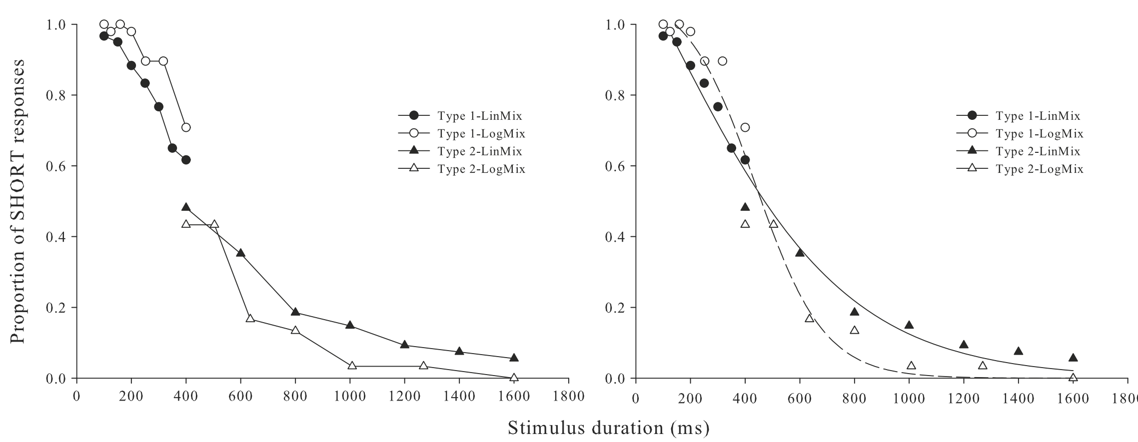

Fig. 7 Mean proportion of SHORT responses as a function of stimulus duration for Type 1 ($S_1 = 100$ ms vs. $L_1 = 400$ ms) and Type 2 ($S_2 = 400$ ms vs. $L_2 = 1{,}600$ ms) bisections and for the inaccurate intermixed bisection performance. *Left panel* functions plotted separately. *Right panel* functions treated as a single one; the *continuous* and *dashed lines* are the global best-fitting psychometric functions for data from the LIN and LOG groups, respectively

Table 5 Bisection points (in ms), difference limen and Weber ratio based on global fits for data from inaccurate intermixed bisection performance

Index	Group	
	LIN	LOG
Bisection point	470.89	459.77
Difference limen	235.89	125.59
Weber ratio	0.50	0.27
Adjusted R^2	0.98	0.97

performed in a way that Type 2 bisection looked like a continuation of Type 1 bisection so that the two stimulus duration sets were treated as single integrated set from a single integrated bisection. Moreover, when treated this way, the best-fitting sigmoidal functions (Eq. 1) yielded good fits (both p's < 0.05; see Fig. 7, right panel). Table 5 presents global index estimates based on the best-fitting parameter estimates: the R^2 index is high for both fits and those global fits also yielded two very similar bisection points between the groups, which is similar to the results from the analyzable data sets. However, the slope of the LIN function is less than the slope of the LOG one, and this can be related to the values of the Weber ratio: for LIN group it is higher than that for the LOG group.

Double temporal bisection

Figure 8 shows the mean proportion of LONG responses as a function of stimulus duration for the two spacing groups in the double bisection phase. Both psychometric functions rise almost equally as a sigmoidal shape and from 0 to 1. Bisection points, difference limen and Weber ratios per group were also calculated (see Table 6).

When they were analyzed, there were no differences between spacing groups for any of the parameters (for the bisection point,[3] $t_{(39)} = 0.02$, $p > 0.05$; for the difference limen, $t_{(39)} = 0.41$, $p > 0.05$; for the Weber ratio, $t_{(40)} = 1.09$, $p > 0.05$).

Besides this, an additional test of the scalar property was conducted by superposing the psychometric functions from Type 1 and Type 2 bisections presented alone (phases 1 and 2), and from double bisection phase (see Fig. 9). (Although this analysis is not a test of any of LeT's predictions, it was conducted in order to test whether the scalar property was replicated or not in humans with different *L/S* ratios.) Since *L/S* ratios are different among bisection types—4:1 for bisections presented alone and 16:1 for double bisection—relative stimulus durations were

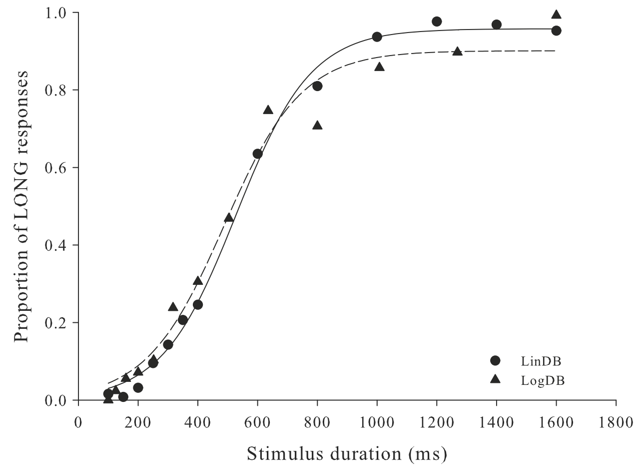

Fig. 8 Mean proportion of LONG responses as a function of stimulus duration for the two spacing groups in the double bisection phase. The *continuous* and *dashed lines* are the global best-fitting psychometric functions for data from the LIN and LOG groups, respectively

Table 6 Mean (and standard deviations) bisection points (in ms), difference limen and Weber ratio for each spacing group in the Double Bisection phase

Parameters	Group	
	LIN	LOG
Bisection point	533.77 (137.45)	535.14 (248.47)
Difference limen	117.99 (120.13)	102.21 (132.17)
Weber ratio	0.20 (0.14)	0.16 (0.11)

calculated by dividing all stimulus durations only by the corresponding bisection point for each bisection type. Visual inspection suggests that almost all psychometric functions superpose, except for psychometric functions from the double bisection phase; instead, these have a flatter slope in comparison to the others.

When Weber ratios from these phases were compared (see Table 7) with a 2 × 3 mixed ANOVA, there was a significant effect of phase ($F_{(2,80)} = 4.13$, $p < 0.05$); and planned comparisons revealed that Weber ratios were higher for double bisection than for the other two phases ($F_{(1,40)} = 6.27$, $p < 0.05$). There were no effects for either stimulus spacing ($F_{(1,40)} = 0.55$, $p > 0.05$) or for the interaction ($F_{(2,80)} = 0.71$, $p > 0.05$).

Location of the bisection points

Finally, one of LeT's predictions concerns the location of the bisection point: LeT predicts that bisection point is slightly higher than the geometric mean of the reference durations. The obtained values for the bisection points tend to be closer to the geometric mean (GM) of the reference durations in all phases. Following Wearden and Ferrara

[3] Data from a single participant in the LOG group who represented an outlier were excluded in order to correct a bias in the LOG group's mean bisection point.

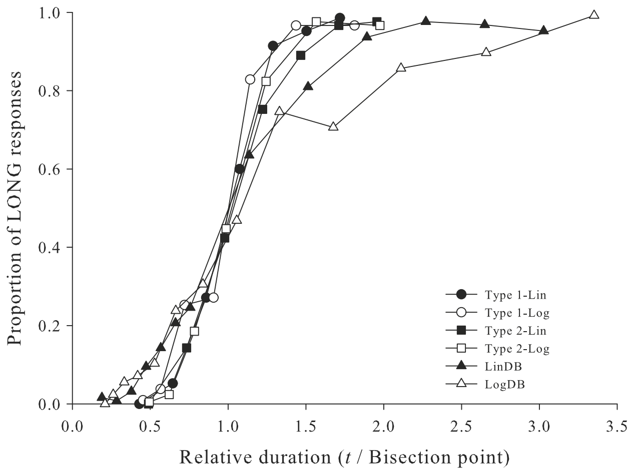

Fig. 9 Mean proportion of LONG responses plotted against relative stimulus duration for the two spacing groups in Type 1 ($S_1 = 100$ ms vs. $L_1 = 400$ ms), Type 2 ($S_2 = 400$ ms vs. $L_2 = 1{,}600$ ms) simple bisections alone and the double bisection (DB) phases

Table 7 Mean (and standard deviations) Weber ratios for each spacing group in Type 1, Type 2 simple bisections alone, and double bisection

Parameters	Group	
	LIN	LOG
Weber 100–400	0.12 (0.07)	0.10 (0.09)
Weber 400–1,600	0.13 (0.09)	0.11 (0.07)
Weber DB	0.19 (0.14)	0.14 (0.09)

(1996), one way of testing this trend is to divide the bisection points by the GM value (call this fraction K_{GM}), thus expressing the bisection points as a proportion of GM. If the bisection point is equal to GM, then $K_{GM} = 1$, values greater than 1.0 indicate that bisection points are above the GM and values lower than 1.0 are below the GM. The same thing can be done for the arithmetic mean (AM; call this fraction K_{AM}).

Figure 10 shows the mean K proportions and their standard errors as a function of phase 1, 2 and double bisection (DB) for both stimulus spacing groups. The horizontal line denotes the K value at which bisection point is equal to either the geometric mean (circles) or to the arithmetic mean (triangles). As can be seen, $K_{GM} > K_{AM}$, suggesting that the bisection points are located between GM and AM. In order to compute and compare the K proportion that best describes the location of the bisection points, departures from 1 for all individual K proportions were taken, and the logarithm of these departures were analyzed in a $2 \times 2 \times 3$ mixed ANOVA, with stimulus spacing as between-subject factor, and mean and phase as within-subject factors.

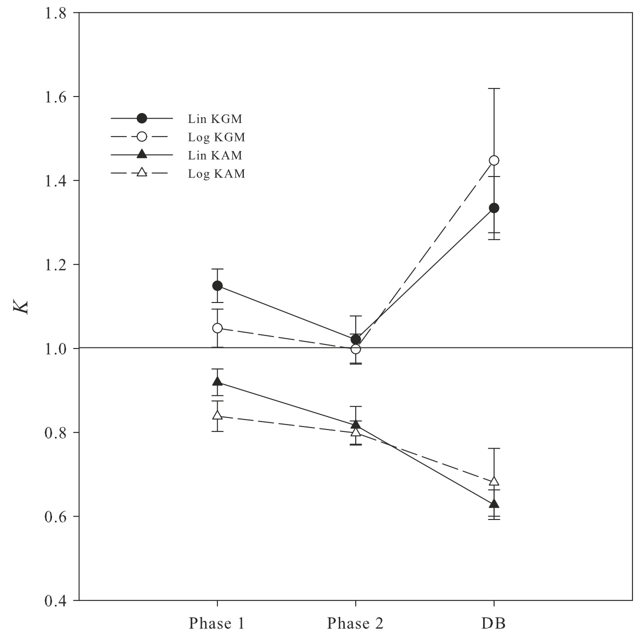

Fig. 10 Mean K proportions for the two spacing groups as a function of phases. *Vertical bars* denote standard error of means. The *horizontal line* denotes the K value at which bisection point is equal to either GM (K_{GM}, *circles*) or AM (K_{AM}, *triangles*). (*Phase 1* = Type 1 bisection ($S_1 = 100$ ms vs. $L_1 = 400$ ms); *Phase 2* = Type 2 bisection Type 2 ($S_2 = 400$ ms vs. $L_2 = 1{,}600$ ms); *DB* double bisection. See text for details)

The analysis revealed a significant effect of phase ($F_{(1.95,\ 77.81)} = 26.29$, $p < 0.05$) and a mean × phase interaction ($F_{(1.69,\ 67.48)} = 6.42$, $p < 0.05$).[4] Post hoc Scheffé test showed that K proportions for double bisection phase has the highest departures from 1 when compared to all other K proportions ($p < 0.05$); moreover, K_{AM} in phase 1 has a higher departure from 1 when compared to K_{GM} in phase 1 ($p < 0.05$); and finally, K_{GM} in the DB phase has a higher departure from 1 when compared to K_{AM} in phase 1 ($p < 0.05$). (Note that, other than this, there is no clear description of the location of the bisection point.)

Discussion

General results in human temporal bisection

In this experiment, analyses of bisections presented alone (phases 1 and 2) reflect some of the usual results in human temporal bisection (Allan, 1998, 2002a, 2002b; Allan & Gerhardt, 2001; Allan & Gibbon, 1991; Ortega & López, 2008; Wearden, 1991; Wearden & Bray, 2001; Wearden & Ferrara, 1995, 1996): (1) the psychometric function has a

[4] Since sphericity assumption was not reached, the Geisser and Greenhouse correction was applied.

sigmoidal shape (see Fig. 3), (2) there is good superposition of all psychometric functions (see Fig. 4), and this improves when normalized by the bisection point (although in order to compare with previous reports, we also normalized by the shortest duration, resulting in not such a good superposition); and (3) constancy of Weber ratio, indicating that the slope of the psychometric functions are the same and *ergo*, where temporal sensitivity is constant.

However, there was no stimulus spacing effect in either of the phases of the experiment. In spite of the fact that other studies have shown that a logarithmic spacing shifts the psychometric function to the left when compared to that of linear spacing (Allan, 2002b; Wearden & Ferrara, 1995, 1996; see Penney et al., 1998, for a theoretical analysis), the present results did not show this effect, even though a large *L/S* ratio (4:1) was employed. Although Penney et al. (1998) proposed that logarithmically spaced stimulus durations can result in durations being represented in memory as more similar to the shortest duration, the present results do not suggest this is the case: rather they suggest that durations from both stimulus spacing types were equally represented. Furthermore, consider the double bisection phase: since the shortest duration was 100 ms and the longest duration was 1,600 ms, the *L/S* ratio was 16:1; but not even with a ratio this large was it possible to observe a spacing effect.

Now, the location of the bisection point is not specific, but the analysis of *K* proportions suggests that bisection points are closer to the geometric mean of the reference durations (and as the bisection points for mixed bisections were not statistically different from those for simple bisections, the same thing applies for mixed bisections). As a result, the stimulus range effect which states that as the *L*–*S* range increases the bisection point will approach AM (Wearden & Ferrara, 1996), did not occur. The apparent reason for this was the great variability in the subjects' responses. Allan (2002a) and Allan and Gerhardt (2001) present similar results: there was no consistency in the location of the bisection point, but its varying location fell somewhere between GM and AM. Moreover, Grondin et al. (2005) found that the standard deviation of the mean bisection points increased when more reference durations are employed within the same block. Both previous experiments and the present one employed complex procedures, where participants had to complete the entire experiment in one session, so that it's possible that task complexity diminished discrimination accuracy.

Additionally, when psychometric functions for simple and mixed bisections were compared, discrimination accuracy diminished when both bisections were presented simultaneously. This is evidenced by three facts: (1) the psychometric function for Type 1 bisection ($S_1 = 100$ ms vs. $L_1 = 400$ ms) does not decay to zero when presented simultaneously, but when presented alone it does; (2) the psychometric function for Type 2 bisection ($S_2 = 400$ ms vs. $L_2 = 1{,}600$ ms) does not decay from 1 when presented simultaneously, but when presented alone it does; and (3) the difference limen was higher for Type 1 bisection when presented intermixed, than when presented alone (see Tables 2, 3). Thus, changes in durations had to be greater if participants were to detect them. Once again, these results concur with those of Grondin et al. (2005).

Mixed bisections

This experiment analyzed human performance in an adaptation of the double bisection task. Previous studies on the double bisection task (Arantes, 2008; Arantes & Machado, 2008; Machado & Arantes, 2006; Machado & Keen, 1999; Machado & Pata, 2005; Maia & Machado, 2009; Oliveira & Machado, 2008, 2009) have found that the psychometric functions for trained temporal bisections presented intermixed do not superpose when plotted against relative stimulus duration (obtained by dividing each duration by the shortest duration); instead, the functions with the largest *S* and *L* values have a steeper slope.

In the present experiment, results from previous studies were replicated: as predicted by the LeT (Machado, 1997; Machado & Keen, 1999), psychometric functions from Type 1 bisection have a flatter slope when both simple bisections were presented within the same block (phase 3), and this is reflected in the increment of the Weber ratio when Type 1 bisection was presented simultaneously, compared to when it was presented alone. Besides, as Grondin (2005) and Grondin et al. (2005) have found, the psychometric functions with the lowest stimulus durations (Type 1 bisection) are over those with the highest durations (Type 2 bisection; see Fig. 6). This effect has been found even when different reference durations are mixed between sessions but not within the same session (Allan, 2002a). Previous studies and the present results suggest that all durations of Type 1 bisection were perceived as "short" when compared to those of Type 2 bisection and vice versa: all durations of Type 2 bisection were perceived as "long" when compared to those of Type 1 bisection.

According to Grondin (2005), the reason for this result is that temporal memory for both referents overloads when referents from two ranges are presented simultaneously. Grondin employed a partition method to test it, where two reference durations were presented at the same time, revealing a lack of superposition of psychometric functions, as was the case with the results from the mixed bisections phase of this experiment. This overloading of temporal memory may also explain the variability between subjects, in terms of the bisection points in all experimental phases and the increment in the difference limen for Type 1 bisection in mixed bisections: a change in durations had to be greater in order to be detected, given the interference in perception caused by previous stimulus durations, on the perception of current duration.

However, there were participants who did not perform the mixed bisections accurately. The result that all durations of Type 1 bisection were perceived as "short" and Type 2 bisection as "long" among participants who performed the mixed bisection phase accurately is even more remarked in participants who did not perform accurately and, in fact, it seems that there was no clear differentiation between the two bisection types as independent of one another when presented in an intermixed fashion. It is interesting to note that average performance of these participants suggests this lack of differentiation between one bisection type and the other, so they performed this phase in a way that suggests that they treated the two bisection types like a single one (see Fig. 7, left panel) even though the temporal markers denoted the correspondence between a stimulus duration and a particular bisection type. It seems that they did not generalize what they encountered in the previous phases to the mixed bisections phase, and therefore they treated it like a single partition task in a way similar to participants from Grondin's experiments (Grondin et al. 2005). The global best-fitting psychometric functions assuming one bisection type as a continuation of the other suggest the same thing (see Fig. 7, right panel). Moreover, notice that the global bisection points calculated from these global fits are very close to the GM of the shortest and the longest durations presented in this phase, that is, $S = 100$ ms, $L = 1{,}600$ ms, and $GM = 400$ ms (compare it to bisection points presented in Table 5). In view of the possibility of partition performance and on global fits, one possible explanation is that nowhere in the given instructions was an indication that the previously encountered phases should be taken into account to perform the mixed bisections phase, which could force these participants to search new S and L reference durations across the whole duration sets of the two bisection types as the mixed bisections elapsed in the block.

But even though these participants did not perform the mixed bisection like those whose data sets were analyzable, the patterns of responding follow similar trends between the two data sets: a decrease in the proportion of SHORT responses in both bisection types as stimulus duration grows, so the timing system of these participants is executing similar processes as the one of the rest of the participants. If SET is consider to describe the results of these participants, the form of the best-fitting global psychometric function and the global obtained bisection points suggest that they are also doing a comparison of the just recently experienced stimulus duration X_T against the two samples of remembered durations: one short duration X_S (where $S = 100$ ms) and another long duration X_L (where $L = 1600$ ms), and when the ratio X_S/X_T became greater than the ratio X_T/X_L then X_T was judged as more similar to X_S and the participants were more likely to respond S. As a result, this ratio comparison postulated by SET predicts the bisection point to equal $X_T = \sqrt{(X_S \times X_L)}$, which is very close to the global bisection points obtained for these participants. In the case of LeT, early states were the most active after a short duration, so they became coupled mainly with the S response due to previous experience with $S = 100$ ms and less with the L response; conversely, later states were the most active after a long duration, so they became coupled mainly with the L response due to previous experience with $L = 1600$ ms and less with the S response. Therefore, it seems that participants who did not perform the mixed bisections accurately took into account only these two stimulus durations and the associations with their corresponding behavioral states to complete the mixed bisections. However, in the case of LeT some considerations must be taken into account concerning this description, which will be addressed in the next section.

Double bisection

The critical result in the double bisection experiments is the psychometric function related to the appearance of two response options associated with the same absolute duration (that is, when $L_1 = S_2$; see Fig. 1). According to Machado (Arantes & Machado, 2008; Machado & Keen, 1999; Machado & Pata, 2005; Oliveira & Machado, 2008), SET predicts indifference to any stimulus duration, whereas LeT predicts a monotonic growing function as stimulus duration increases. All previous experiments (Arantes, 2008; Arantes & Machado, 2008; Machado & Arantes, 2006; Machado & Keen, 1999; Machado & Pata, 2005; Maia & Machado, 2009; Oliveira & Machado, 2008, 2009) have found that LeT's predictions are fulfilled. Our experiment shows similar results: the proportion of LONG responses grows as a function of stimulus duration (see Fig. 8). It should be noted that the double bisection phase is similar to a partition method (Wearden & Ferrara 1995, 1996) with a L/S ratio equal to 16:1, that is, stimulus duration had to be classified without well distinguished referents, but all the same discrimination was apparent (Allan, 1998). Our results support these previous ones.

Nevertheless, consider the durations participants faced: LeT has been tested with stimulus durations above 1,000 ms, but participants in this experiment faced durations as low as 100 ms, so care must be taken about interpretation of data in terms of LeT's assumptions. There is a proposal in the context of Killeen and Fetterman's (1988) Behavioral Theory of timing (BeT) concerning very short stimulus durations which states that there are no accumulated pulses from an internal clock at durations as low as 100 ms, so the probability of correctly respond to that durations reduces to a simple exponential decay function (Raslear, Shurtleff, & Simmons, 1992). In the context of LeT, this same exponential decay function could also be assumed for the present results since LeT's and BeT's assumptions are closely related, but care must still be taken because an additional assumption concerning the influence of reinforcement rate on clock rate should be made in order to obtain this reduction, an assumption not tested in this experiment. Future research could test this possibility by manipulating this additional assumption in humans.

An alternative explanation comes from a suggestion by Church and Deluty (1977, pp. 226): what if participants are just generalizing a previously learned response across similar tasks, that is, responding in a relative way? If this is the case, then it is to be expected that a task which is similar to those previously performed favors the application of the same response rule. This is an instance of *transposition* (see Lazareva, Wasserman, & Young, 2005). Consider participants' task in the double bisection procedure: across all phases they had to judge whether stimulus duration was short or long, so they had training in multiple pairs of durations, and it has been reported that multiple training enhances transposition (Lazareva, Miner, Wasserman, & Young, 2008). So, this possibility could be tested in future studies.

A second alternative explanation is put forward by Jozefowiez, Staddon, and Cerutti (2009), who postulate that the participant's response in a double bisection task depends on two things: the participant's variable representation x_i of time with a Gaussian distribution centered at the natural logarithm of time t_i, and a payoff function for every response b_i they can emit at any value x_i can take, so the response rule is just the sum of the products between the probability of emitting a response b_i when subjective time is x_i, and the probability of x_i when real time is t_i. In this behavioral economic model of interval timing (BEM), as both response options have an expected value associated with every subjective time x_i, then it does not make sense to respond when x_i is associated with low expected values, and it is expected that the response rate increases when x_i is associated with high expected values. Thus, given that the LONG response option has low expected values at short durations, then the response rate should not be high, but it should rise as the stimulus duration gets longer. This is exactly what Jozefowiez, Staddon and Cerutti found when they applied their model to data from Machado and Pata (2005), and this is exactly what we found in this experiment.

Besides, although SET predicts that all psychometric functions should superpose when normalized by their bisection points (Allan, 1998, 2002b; Allan & Gerhardt, 2001; Penney et al., 1998), those from double bisections phase had a flatter slope relative to those from simple bisections alone when all psychometric functions from simple bisections alone and double bisections were superposed (see Fig. 9). This flatter slope is evidenced by the increment in the Weber ratio for double bisection functions. Previous evidence indicates that Weber ratio does not always remain constant (see Allan, 1998; Wearden & Lejeune, 2008, for a discussion), but there is a lack of specificity concerning how exactly Weber ratio changes across conditions: Allan (1998) and Wearden and Lejeune (2008) have suggested that the slope of the psychometric function decreases as *L/S* ratio increases, thus implying that the Weber ratio increases as reference duration values increase; this result was also found by Lavoie and Grondin (2004). But the generalized form of Weber's law suggests that the Weber ratio should increase as reference durations values *decrease*; this is what happens in the case of sensory systems (Gescheider, 1997), and is also exactly what Fetterman and Killeen (1992) and Grondin (1993) found. The present results concur with previous ones from Allan (1998), Wearden and Lejeune, and Lavioe and Grondin, thus implying that human temporal sensitivity decreases as the *L/S* ratio increases. Lavioe and Grondin have suggested that this diminished temporal sensitivity is due to a limitation in information processing: a double bisection imposes more information to be processed within the same temporal window because it includes durations from all bisections employed, but after performing three previous blocks of trials, the participant's ability to process information from the block of trials from the double bisection phase diminishes, and as in this case temporal memory is already overloaded (Grondin, 2005), this time period became difficult to estimate. Our results support this hypothesis.

Finally, and in contradiction to previous results (Allan, 1998, 2002b; Penney et al., 1998; Wearden & Ferrara 1995, 1996), there was no stimulus spacing effect in the double bisection phase either: even though the *L/S* ratio was large, the psychometric functions for linear and logarithmic spacing are very similar; in fact, they almost superpose. Analyses between spacing groups conducted on the bisection points, difference limen and the Weber ratio did not find any difference between spacing groups. Once again, it seems that all durations are represented in a similar manner.

Conclusion

In summary, the double bisection task was developed by Machado and Keen (1999) for the purpose of comparing SET and LeT in animal timing. Our results accord with some of LeT's mathematical predictions in the example of human timing and presents additional analyses to check how humans arrived at the critical phase of experimentation. Even though the present experiment is not an exact replica of the original double bisection task, the main features of the task were preserved: two single bisection were first trained, keeping the equality of L_1 and S_2 in order to further preserve what Machado and colleagues have emphasized as the critical test trial, that is, the presentation of the two response options associated with the same stimulus duration (both L_1 and S_2 options associated with a 400 ms duration). Following simple bisections, both bisection types were intermixed in the same block of trials, keeping constant the characteristics that permit the organism to differentiate between one bisection type and the other. The fact that some participants did not perform these mixed bisections accurately could imply that the given instructions did not require them to remember what they had already encountered. But it does not necessarily mean that they did not perform the mixed bisection in a similar manner than those who did complete this phase accurately: two possible descriptions in terms of SET and LeT were provided in order to show that the way all participants perform are no different. Finally, following mixed bisections a double bisection phase per se was introduced in which new trial types were introduced by way of a new temporal marker, but the present experiment still maintained the properties of the original double bisection experiments: the "1" key was trained so that it preserved the S_2 property and the "2" key was trained so that it preserved the L_1 property when the new trial type was encountered. And therefore, the present experiment also compared a choice between a SHORT response and a LONG response, like Machado and colleagues have done. Since the present results coincide on those of previously reported experiments employing the double bisection procedure, the same processes employed to describe performance in pigeons could be applied to humans (like the way SET is typically applied to humans).

But although the present results coincide with LeT's predictions, the assumptions inherent in the underlying LeT processes should be cautiously considered on human data because the way LeT describes temporal control of behavior in nonhuman animals does not necessarily apply to human participants due to the very short temporal durations employed in human timing research. Thus, alternative explanations have been proposed here (assuming other underlying processes): (1) humans are applying the same response rule when faced with the same task but with different values (transposition); (2) humans perform according to the expected value every response b_i has at subjective time x_i given reinforcement contingencies, responding more to times where expected values are higher. Future research could shed light about these possibilities by experimental manipulations of variables like manipulation of the physical properties of the response options (see Lazareva et al., 2008) or variations in reinforcement rate (via manipulating intertrial intervals; see Raslear et al., 1992).

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