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Temporal Bisection in Children

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Children aged 3, 5, and 8 years received training on a temporal bisection task, with standard short and long durations being presented as visual stimuli lasting 1 and 4 s or 2 and 8 s. Nonstandard comparison stimuli were spaced linearly between the standards. Psychophysical functions showed increasing proportions of "long" responses (responses appropriate to the long standard) with increasing stimulus duration, but were flatter in the younger children than in the 8-year-olds. Bisection points (the stimulus duration giving rise to 50% "long" responses) were close to the arithmetic mean of the short and long standards in most conditions. Statistical analyses and results from different theoretical models of the data all suggested that temporal sensitivity was higher in the 8-year-olds than in the younger groups, even when the possibility of random responding was controlled for.

Key Words: temporal bisection; timing behavior; children; scalar timing.

A recent article by Block, Zakay, and Hancock (1999) highlighted the paucity of developmental studies of simple time perception. This may be in part explained by the influence of the Piagetian framework according to which a child's estimation of time depends on the development of the capacity to integrate different sorts of information, such as that involving distance, time, and speed (e.g., Levin, 1992). In this type of task, children's difficulties with temporal judgment seem more appropriately attributed to general cognitive limitations in coordinating information than on a specific problem of time perception (Levin, 1977, 1979; Richie & Bickhard, 1988; Wilkening, Levin, & Druyan, 1987), and children below the age of about 8 years may lack the necessary cognitive skills to perform well on the tasks used.

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However, researchers have reported temporal judgments from younger children when duration production or reproduction tasks are used (e.g., Bentall, Lowe, & Beasty, 1985; Crowder & Hohle, 1970; Droit-Volet, 1999; Fraisse & Orsini, 1958; Matsuda & Matsuda, 1983). Unfortunately, these methods, which use the temporal characteristics of responses such as their duration or spacing, may inaccurately assess young children's temporal abilities because of the children's difficulties in inhibiting their responses. Supporting this view, some studies have shown that when problems of inhibition of responses are diminished by the development of collateral behaviors (Pouthas, 1981, 1985) or by extensive training with external supports (Droit, 1994, 1995) the temporal regulation shown by young children improves.

A method which might help us to understand temporal abilities of children as young as 3, while minimizing problems of inhibition, is the temporal bisection method initially developed for use with rats (Church & Deluty, 1977) and later modified for human adults (Wearden, 1991). In bisection tasks with humans, participants initially receive repeated presentations of two standard stimulus durations (identified as short and long standards) and then classify a range of durations (short and long, as well as intermediate stimuli) in terms of their similarity to short and long. The usual method of presenting data from such tasks is to derive a psychophysical function consisting of the proportion of "long" responses (i.e., classifications of a duration as more similar to long than to short) plotted against stimulus duration. Figure 1 shows some psychophysical functions which, while invented as illustrations, are typical of results obtained.

What might developmental changes in bisection performance look like? The upper panel of Fig. 1 shows one possibility, where different conditions (e.g., different age groups) produce psychophysical functions which clearly differ in slope. In bisection, the slope of a psychophysical function is an index of the sensitivity to time manifested in the behavior observed, with steeper slopes indicating greater sensitivity. The first developmental possibility is some systematic change in sensitivity to duration, manifested in changes in psychophysical function slope, with changing age. More precisely, sensitivity to duration might increase with age, eventually reaching a level similar to that shown by adults.

The lower panel of Fig. 1 shows a different possibility. Here, the two psychophysical functions have very similar slopes, but one shows higher proportions of "long" responses to intermediate-duration stimuli than the other: the two psychophysical functions have the same slope, but one is laterally displaced, at least over the middle part of its range, relative to the other. Such curves are considered to differ in terms of *bias* toward responding "long" or "short" rather than sensitivity. One measure of this bias is the bisection point, the stimulus value that gives rise to 50% "long" responses. In the upper panel of Fig. 1, the curves have identical bisection points, but different sensitivities; in the lower panel the bisection points differ but sensitivity does not. Thus, our second developmental possibility is some shift of the psychophysical function laterally reflecting a developmental change in bias toward responding "long" or "short."

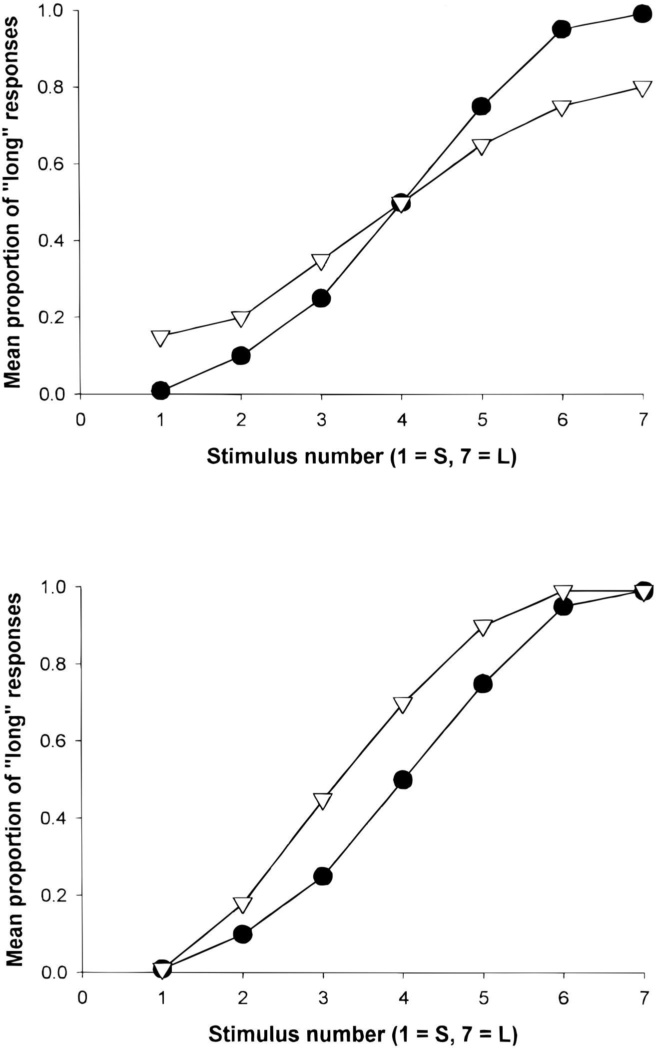

FIG. 1. Invented psychophysical functions to illustrate potential developmental changes. The mean proportion of "long" responses is plotted against stimulus duration. Stimulus number 1 is the short standard and stimulus number 7 the long standard, with durations spaced in equal linear steps between them. Upper panel: psychophysical functions differing in sensitivity but not bias toward responding "long." Lower panel: psychophysical functions differing in bias but not sensitivity.

The two developmental change possibilities illustrated are distinct in the sense that shifts in bisection point are not related to temporal sensitivity, nor are changes in slope related to bias. However, they are not mutually exclusive, so younger children could differ in both behavioral sensitivity and bias from older ones.

There are several models accounting for performance on bisection tasks (e.g., Allan & Gibbon, 1991; Wearden, 1991; Wearden & Ferrara, 1995) which are based on scalar timing theory (Gibbon, Church, & Meck, 1984; Wearden, 1994). Scalar timing theory proposes that the raw material for time judgments comes from a pacemaker-accumulator internal clock. However, the models also involve memory and comparison processes. In the case of bisection, for example, the stimulus just presented is assumed to be stored in a working memory mechanism derived directly from the accumulator of the clock, whereas the standard short and long standard durations are stored in a longer-term reference memory.

More specifically, the *modified difference model* of Wearden (1991) assumes that the decision whether to classify some stimulus value, *t*, as more similar to short or long is essentially governed by the difference between *t* and samples taken from long-term memory representations of the short and long standards. Memory representations are stored as distributions rather than single values; therefore, sampling from their distributions produces trial by trial variance. In general, the fuzzier the memory of the short and long standards (i.e., the higher the variability of the distribution), the flatter the observed psychophysical function will be. The variability of memory of the short and long standards is thus a kind of sensitivity parameter controlling the slope of psychophysical functions.

In the developmental psychology of time, memory for duration per se has been largely neglected (Droit-Volet & Rattat, 1999). We suggest nevertheless that any observed increase in timing sensitivity with increasing age might in part be related to developmental changes in temporal memory representations (i.e., reduced variability of the long-term memory representations of the short and long standards). In this article, the modified difference model of Wearden (1991) is used to model obtained data and this allows a potential answer to the question of whether there are developmental changes in temporal memory representations.

Two psychophysical functions can differ in slope (cf. upper panel of Fig. 1) because of different variability of memory representations, because of random responding, or both. Here, random responding would mean that “long” and “short” responses were emitted with equal probability without regard to the stimulus duration presented on a trial, thus flattening the psychophysical function. In determining the behavioral sensitivity to changing duration, different variabilities of memory representations and different levels of random responding are to some degree confounded, as both increasing memory variability and increasing amounts of random responding tend to flatten observed slopes. Modeling suggests, however, that the strongest impact of random responding is felt at the extremes of the psychophysical functions (that is, in responses to the short and long standards). In bisection with adults, the long and short standards are hardly ever confused (i.e., the short standard produces nearly zero “long” responses and the long standard nearly 100%), so random responding is not believed to play any significant role in the bisection performance of adults (Wearden, 1991). However, children may be quite different, with some significant proportion of trials occurring in which the child responds without timing the stimulus presented at all. A second model tests this possibility by using a version of the modified difference model with the addition of random responding.

There is only one previous study of temporal bisection in children, which used children of 5, 8, and 10 years of age, and short durations, a short/long pair of 200/800 ms (McCormack, Brown, Maylor, Darby, & Green, 1999). In that study, the psychophysical functions were flatter in the 5-year-olds than in older children, whose behavior was very similar to that of adults. That is, there was an apparent increase in temporal sensitivity with increasing age. There was, however, no developmental change in bisection point values, and these were located close to the arithmetic mean of the short and long standards, a result commonly obtained in temporal bisection by adults (Wearden, 1991; Wearden & Ferrara, 1995, 1996; Wearden, Rogers, & Thomas, 1997; Wearden, Wearden, & Rabbitt, 1997), although not universally found (e.g., Allan & Gibbon, 1991).

The main aims of the present experiment were to extend the study of temporal bisection in children both to a younger population (3 years of age) and to longer durations (from 1 to 8 s) than used previously.

In the study by McCormack et al. (1999) only one range of time values was used, thus precluding tests of whether timing in children conforms to the requirements of scalar timing theory. One general principle of this theory is that the timing of absolutely different time intervals can be seen to be invariant when data are plotted on the same relative scale. A crude example is that although 1 and 1.5 s might be easily discriminated, the same absolute difference between stimuli will not always be equally discriminable: 10 and 10.5 s and 99 and 99.5 s will be obviously harder to tell apart. On the other hand, constant discriminability might be obtained more readily when stimuli have the same proportional difference, so when differences are scaled as a proportion of absolute stimulus value discriminability remains constant as absolute duration varies.

On many timing tasks, conformity to scalar timing is tested by demonstrating superimposition, the fact that data from different absolute duration ranges might superimpose when plotted on the same relative scale. For bisection, Allan and Gibbon (1991) suggest that the appropriate test for superimposition is that psychophysical functions superimpose when absolute durations are plotted as a proportion of the bisection point for the condition in force, and this method will be used here. If superimposition occurs, the sensitivity of the underlying timing process is shown to be constant as absolute duration varies. As superimposition can only be tested by using more than one range of time values, our experiment employed bisection tasks with two duration ranges (1–4 s vs 2–8 s).

METHOD

Participants

The participant sample was composed of 48 children. These made up three equal-sized age groups, each consisting of 8 boys and 8 girls: (1) a 3-year-old group (mean age = 3.6 years, *SD* = 0.33), (2) a 5-year-old group (mean age =

5.5 years, *SD* = 0.29), and (3) an 8-year-old group (mean age = 8.6 years, *SD* = 0.71). All children came from nursery and primary schools in Clermont-Ferrand, France.

Materials

The children were tested individually in a quiet room in their schools. A PowerMacintosh computer with a color monitor screen controlled experimental events and recorded data with Psyscope (Cohen, McWhinney, Flatt, & Provost, 1993). Responses were made on the left (red) and right (green) buttons of a Psyscope response box, with the central (yellow) button being hidden. Two paper circles, a smaller and bigger one, were stuck above the response buttons corresponding to the short and long standards in the bisection task. The stimulus used for the bisection task was a blue filled circle, 4.5 cm in diameter, presented in the center of the computer screen. During the training phase, postresponse feedback was given in the form of a picture of a clown who was either smiling (after correct responses) or frowning (after incorrect ones). The clown picture was presented in the center of the monitor screen and was displayed for 2 s.

Procedure

Half the children in each age group (4 boys and 4 girls) were arbitrarily assigned to the 1/4-s bisection condition, and the other half to the 2/8-s bisection condition. For the 1/4 s condition, short was 1 s and long was 4 s. The nonstandard stimulus durations were 1.5, 2, 2.5, 3, and 3.5 s. In the 2/8-s condition, short and long were 2 and 8 s, and the nonstandard durations were 3, 4, 5, 6, and 7 s.

The children received three successive phases: pretraining, training, and testing. In pretraining, the child was shown the short and long values appropriate for their duration group, with each standard being presented five times in alternation. These stimuli were accompanied by instructions given by the experimenter. For short these were “Look, it’s the short circle. It stays on for a short time.” For long these were “Look, it’s the long circle. It stays on for a long time.”

During the training phase, the child was trained to press one button on the response box (that associated with the small circle) after short and the other button (associated with the larger circle) after long. The association of short and long with the left and right response buttons was counterbalanced. Each child was given successive blocks of eight trials, with each standard duration having a 50% probability of appearance on each trial, with an intertrial interval that was a randomly chosen value between 1 and 3 s. A correct response resulted in the appearance of the smiling clown and an incorrect one the appearance of the frowning clown and repetition of the trial events. Training terminated when the child made no errors during a block of eight trials. If more than three training blocks were required, training was continued the following day.

The testing phase was given on the same day just after a successful training block. It maintained the conditions of training, except that the feedback was discontinued. The experimenter said “It’s the same game, but now the clown isn’t here to tell you whether or not you've played well." Each child received 10 blocks of 7 trials, the short and long standards being presented one each per block, as well as the intermediate-duration stimuli. The stimuli within each block were presented in a random order.

RESULTS

Performance Measures

Table 1 shows the number of children in the different age groups meeting the training criterion (eight consecutive correct responses to the short and long standards) in from one to six training blocks. The 8-year-olds took at most two training blocks, the 5-year-olds up to three blocks, and the 3-year-olds up to six. A Kruskal–Wallis test showed that the number of blocks needed varied significantly with age, $\chi^2(2) = 6.92$, $p < .05$, and between-age comparisons using Mann–Whitney U tests found a significant difference between 3- and 8-year-olds, $U = 71$, $p < .05$, whereas neither the difference between the 3- and 5-year-olds nor the difference between the 5- and 8-year-olds was significant (Mann-Whitney $U = 90$ and 101, $p = .20$ and $p = .16$, respectively)

Figure 2 shows the mean proportion of "long" responses during the testing phase, plotted against stimulus duration. Inspection of individual psychophysical functions showed that one 3-year-old child in the 1/4 s condition and one 5-year-old in the same condition produced very disorderly functions. Data from these two children were dropped for calculation of the means shown in Fig. 2 and all subsequent analyses. No other children were excluded for any other reason (e.g., chronometric counting). The upper panel shows data from the 3-year-olds, the center panel data from the 5-year-olds, and the lower panel data from the 8-year-olds. Inspection of the results shows that all psychophysical functions were orderly and that the mean proportion of "long" responses increased monotonically with stimulus duration at both the standard short/long pairs used and whatever the age of the children tested. Inspection of the averaged psychophysical functions suggests, however, that there might be age effects on the steepness of their slope, with the older children producing psychophysical functions which increased more abruptly with increasing stimulus duration.

TABLE 1
Number of Children in Each Age Group Requiring Different Numbers of Training Blocks to Meet the Learning Criterion (8 Consecutive Correct Responses) in the Training Phase

Number of blocks required	3-year-olds	5-year-olds	8-year-olds
1	7	10	13
2	3	4	3
3	1	2	0
4	4	0	0
5	0	0	0
6	1	0	0

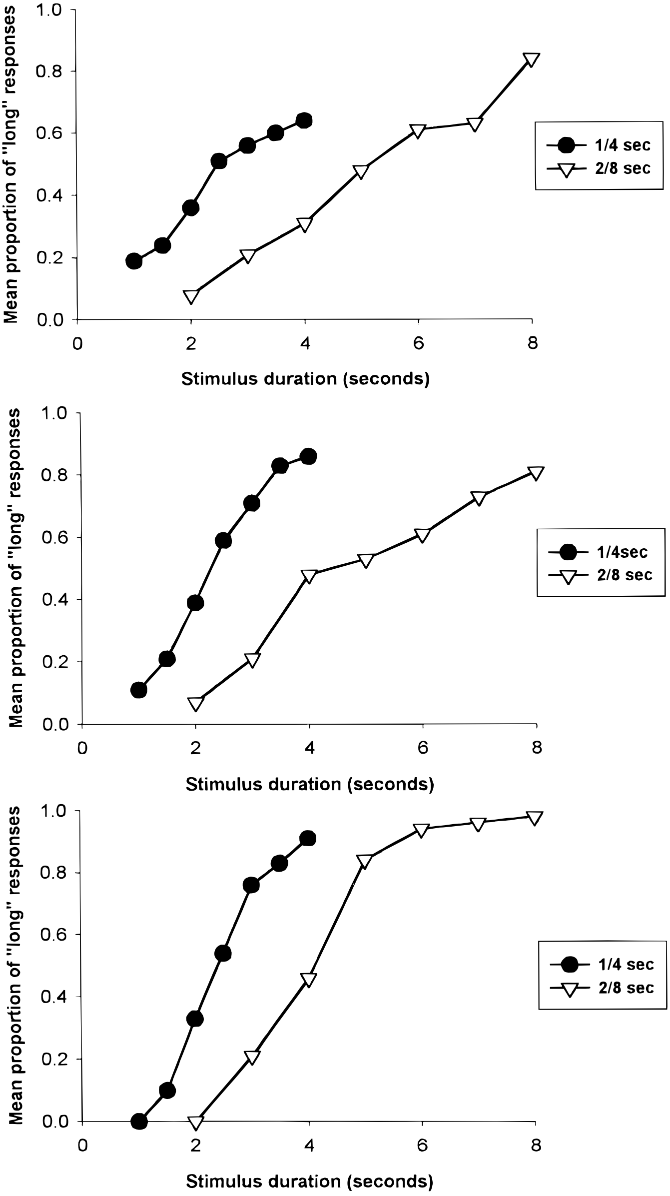

FIG. 2. Mean proportion of “long” responses plotted against stimulus duration from the testing phase of the experiment. Data are shown separately for the 1/4-s and 2/8-s bisection conditions. Upper panel: data from the 3-year-olds; center panel: data from the 5-year-olds; lowest panel: data from the 8-year-olds.

An analysis of variance conducted on the proportion of “long” responses using age-group and stimulus duration as factors found, for the 1/4-s conditions, that the age-group effect was not significant, $F(2, 19) = 0.61$, but obtained a significant effect of stimulus duration, $F(6, 114) = 81.6$, $p < .001$, and a significant age-group × stimulus duration interaction, $F(12, 114) = 3.09$, $p < .001$. This latter result statistically supports the suggestion that the psychophysical functions for the different age groups differed in shape, although another more detailed analysis is presented later. The same analysis on data from the 2/8-s conditions produced the same pattern of results: there was no significant effect of age-group, $F(2, 21) = 1.67$, but there was a significant effect of stimulus duration, $F(6, 126) = 102.56$, $p < .001$, and a significant age-group × stimulus duration interaction, $F(12, 126) = 3.74$, $p < .001$. All age groups showed significant increases in the proportion of “long” responses with increasing stimulus duration, smallest $F(6, 36) = 10.02$, largest $F(6, 36) = 78.63$, both $p < .001$.

Similarities and differences between the psychophysical functions produced by children of different ages and in different conditions were examined by calculating the bisection point and Weber ratio from the psychophysical functions. The bisection point is the stimulus duration giving rise to 50% “long” responses. There are various ways of calculating the bisection point (Wearden & Ferrara, 1995), but these generally yield nearly identical results. Here, we used the regression method introduced by Church and Deluty (1977) and employed by various authors since (Wearden, 1991; Wearden & Ferrara, 1995, 1996). The data used were the psychophysical functions produced by the different groups as a whole (i.e., the functions shown in Fig. 2). Linear regression of the part of the psychophysical function that was steepest was used to derive slope and intercept parameters, and these were used to calculate the bisection point. For example, consider the psychophysical functions shown in the upper panel of Fig. 1. For both functions shown, the proportion of “long” responses was flatter at the extremities of the curve than in the middle. The steepest part comes from the stimulus 3–6 range for the steeper function and the stimulus 2–5 range for the flatter one, and these parts of the curve would be used to calculate the regression line. All regressions calculated on our data produced r^2 values of at least 0.95. The resulting bisection point values are shown in Table 2 and can be compared with the arithmetic mean (average of the short and long standards) and the geometric mean (square root of the product of the short and long standards) for the 1/4- and 2/8-s conditions.

It is clear from Table 2 that most bisection points (all from the 1/4-s conditions and two of the three from the 2/8-s conditions) were closer than the geometric mean to the arithmetic mean of the short and long standards, although the 8-year-olds in the 2/8-s condition produced a bisection point very close to the geometric mean. Also shown in Table 2 is the *Weber ratio*, a measure of the steepness of the psychophysical function which is an index of temporal sensitivity. This is calculated from the regression line by first determining the *difference limen* (half the difference between the stimulus duration giving rise to 75% “long” responses and

TABLE 2
Bisection Points and Weber Ratios Derived from the Psychophysical Functions Shown in Fig. 2

	1/4 s		2/8 s	
Group	BP	WR	BP	WR
3-year-olds	2.56	0.42	5.21	0.35
5-year-olds	2.32	0.32	5.09	0.41
8-year-olds	2.40	0.23	4.06	0.20

Note. The arithmetic mean for the 1/4-s pair was 2.5 s, the geometric mean 2 s. The arithmetic mean for the 2/8-s pair was 5 s, the arithmetic mean 4 s. BP, bisection point (in seconds); WR, Weber ratio.

that giving rise to 25% "long" responses) and then dividing this difference limen by the bisection point value. Smaller Weber ratios indicate steeper psychophysical functions and hence greater temporal sensitivity. Obviously, the 8-year-old children produced smaller Weber ratios than the two younger groups, consistent with the greater apparent steepness of their psychophysical functions.

However, perhaps the most convincing way of investigating whether there were changes in psychophysical function slopes with increasing age would be to examine slopes from individual subjects in the different age groups. Linear regression was used to determine the slope values, with data points coming from the steepest part of the psychophysical function for each individual child, as discussed above. Consider first data from the 1/4-s bisection conditions. A Kruskal–Wallis ANOVA on the slopes showed an overall between-age difference, $\chi^2(2) = 13.00$, $p = .02$, and subsequent Mann–Whitney tests between pairs of age groups found significant differences between all of them: 3 vs 5 years, $U = 6$, $p = 0.18$; 3 vs 8 years, $U = 2$, $p = .003$; 5 vs 8 years, $U = 8$, $p = .02$. For the 2/8-s bisection conditions, there was an overall difference in slope, $\chi^2(2) = 7.49$, $p = .02$, and between-group Mann–Whitney tests found significant differences between the 3- and 8 year-olds and 5- and 8 year-olds, both Us $= 10$, $p = .02$, whereas there was no significant difference between the slopes of the 3- and 5-year-olds, $U = 25$, *ns*.

Our next analysis tested whether the bisection performance of the children exhibited the *scalar property* of time found in many other data from bisection studies with humans (e.g., Allan & Gibbon, 1991; Wearden & Ferrara, 1996; Wearden, Rogers, & Thomas, 1997) by examining superimposition, the requirement that psychophysical functions from judgments of absolutely different time intervals superimpose when plotted on the same relative scale. Figure 3 shows data from the three age groups when this is done.

Inspection of the data in the different panels of Fig. 3 shows that superimposition was reasonably good, with the data points from the 1/4-s condition and the 2/8-s condition overlapping well, at least in the middle part of the range. Taking the psychophysical functions overall, inspection suggests that the 3-year-olds had steeper functions for the 2/8-s condition than the 1/4-s one, that this difference was reversed for the 5-year-olds, and that there was little difference for the

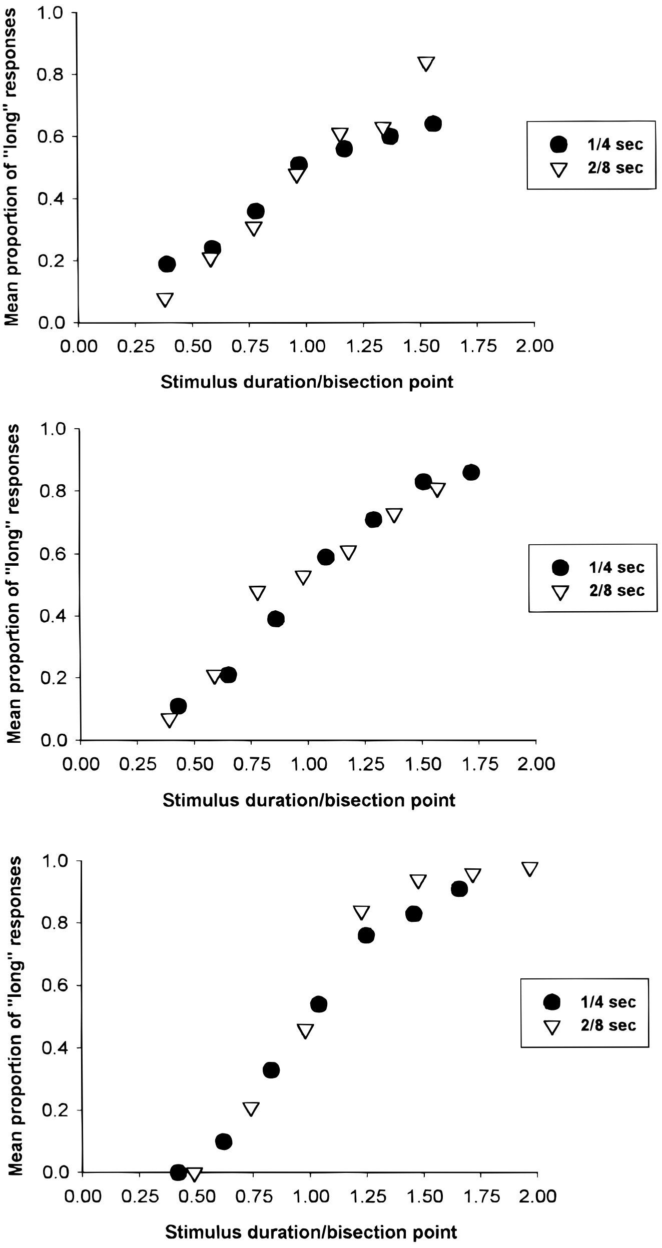

FIG. 3. Psychophysical functions from the three age groups, plotted against stimulus duration, where the stimulus duration is expressed as a fraction of the bisection point (Table 2) for the condition plotted.

8-year-olds. This is consistent with the Weber ratios shown in Table 1, where smaller values indicate steeper functions, and also with a comparison of the slope values produced by individual children in the different conditions. In a comparison of slope values, the only significant difference between the 1/4-s and 2/8-s conditions came from the 5-year-old children.

Modeling of Data

The data in the present experiment were modeled by two different computer simulations. The first was the modified difference model of Wearden (1991). To produce bisection performance this model calculates two differences. One of these, $D(s^*,t)$, is the absolute difference between the stimulus duration to be judged, t, assumed to be timed without error, and s^* , a sample drawn from the long-term memory of the short standard. The other, $D(l^*,t,)$, is the absolute difference between t and a sample drawn from the memory of the long standard, l^*. s^* and l^* differ from trial to trial and are drawn from Gaussian distributions with means equal to the values of short and long standards, respectively, and some coefficient of variation, c, which is one of the two parameters of the model. If the difference between $D(s^*,t)$ and $D(l^*,t)$ is less than some threshold value, b, the model responds “long.” If this difference is greater than b, the model responds “short” if $D(s^*,t) < D(l^*,t)$ and responds “long” if $D(s^*,t) > D(l^*,t)$. b is the second parameter of the model.

Expressed less formally, if the model cannot tell whether t is closer to the short or long standard it responds “long.” If the differences are more clearly discriminated, the model chooses the smaller difference between a standard duration and t. b is thus a kind of bias toward responding “long” which is the default in ambiguous conditions. With b close to zero, the model will bisect at the arithmetic mean of the short and long standards, but larger b values push the bisection point toward the geometric mean or even below it. Using the model examples shown in Fig. 1, the coefficient of variation parameter, c, steepens or flattens the psychophysical function (upper panel), whereas the bias parameter displaces the curve laterally (lower panel) but does not alter the slope.

The modified difference model just described was embodied in a program written in Visual Basic 6 (Microsoft Corporation), and the conditions of the experiment were simulated with 1000 trials with each comparison stimulus being used. c and b were varied over a wide range and the values producing the smallest mean absolute deviations between the simulation and data are shown in the upper part of Table 3. Inspection of the parameter values suggests that c, the coefficient of variation of the representation of the short and long standards, varied with age, being highest in the 3-year-olds and lowest in the 8-year-olds. Here, smaller c values indicate more precise temporal representation, so the variance of remembered times decreases with increasing age. Bias values (b) were usually small, except for the 2/8 s condition with the 8-year-olds, consistent with their bisection point in this condition being close to the geometric mean of the standards. Mean absolute deviation values were generally small (all 0.05 or less), indicating a reasonable fit between the model and data.

TABLE 3
Parameter Values Derived from Fits of the Models Described in the Text to the Psychophysical Functions

	1/4 s				2/8 s			
Group	*c*	*b*	*p*	MAD	*c*	*b*	*p*	MAD
Model 1								
3-year-olds	1.24	0.70		0.03	0.80	0.50		0.04
5-year-olds	0.55	0.40		0.03	0.70	0.20		0.05
8-year-olds	0.46	0.20		0.04	0.25	1.50		0.03
Model 2								
3-year-olds	1.00	0.25	0.20	0.03	0.65	0.25	0.10	0.03
5-year-olds	0.50	0.30	0.10	0.02	0.65	0.20	0.15	0.04
8-year-olds	0.38	0.05	0.01	0.04	0.23	1.60	0.01	0.03

Note. Model 1 is the modified difference model from Wearden (1991); Model 2 is the same model with the addition of random responding. The data points and the best fitting function derived from Model 2 are shown in Fig. 4. *c* is coefficient of variation of the short and long memory representations, *b* the bias toward “long” responses, and *p* (for Model 2) the probability of random responding. MAD is the mean absolute deviation, the sum of absolute differences between the data points and the fitted functions divided by 7, the number of data points.

The second model fitted to the data was identical to the first except for the addition of a parameter, *p*. This was the probability, on each trial, of emitting a response at random (i.e., “short” and “long” responses being equally likely), without regard to stimulus duration. On nonrandom trials, the same rules as the model described above were followed, and all other details were as for the previous model. The lower part of Table 3 shows the parameter values from this model, and Fig. 4 shows fits of the model to data.

The random responding model (model 2 in Table 3) generally fitted data well, with most deviation coming from a single point (as in the 2/8-s conditions from 3- and 5-year-olds). Parameter values for *c* followed the same pattern as for the modified difference model without random responding: higher *c* values were obtained in the younger children than in the older ones. In the random responding version of the model, the bias parameter *b* was usually smaller than in the modified difference model itself, and of small absolute value, except for the 2/8-s condition with 8-year-olds, who needed a larger *b* value to produce their near-geometric mean bisection. Perhaps of most interest is the added parameter, *p*. This was substantial in fits to data produced by the younger children, with between 10 and 20% of responses being generated randomly, but negligibly small for the 8-year-olds. Thus, at least according to this model, part of the reason for the flatness of the psychophysical functions in the younger children results from random “short” and “long” responses which take no account of actual stimulus

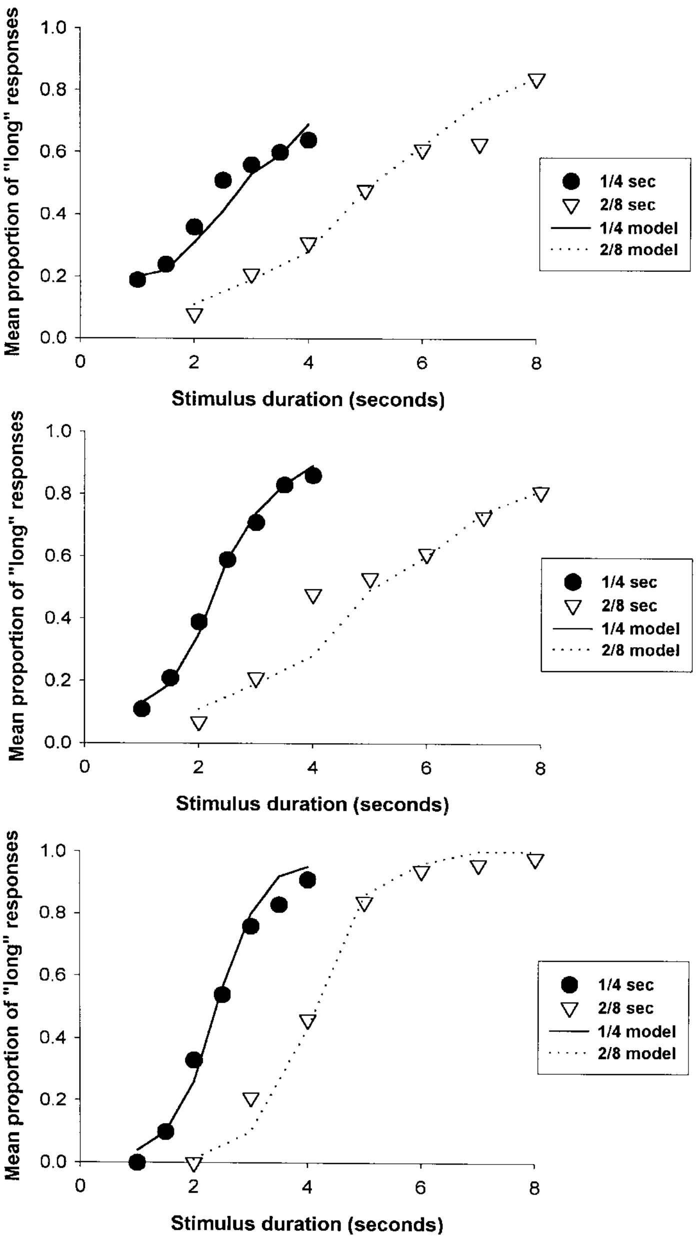

FIG. 4. Unconnected symbols show psychophysical functions from the three age groups (plotted as Fig. 2). Lines without symbols show the best fitting function derived from the modified difference model with random responding (Model 2). Parameter values for the fitted functions are given in the lower part of Table 3.

duration, but these random responses are infrequent in the oldest subjects. It should be noted, however, that according to the model the differential flatness of the psychophysical function is not solely the result of random responding: the variability of remembered standard durations also varies with age.

DISCUSSION

Data presented above support several conclusions. First, the bisection method can yield orderly data from children, even those as young as 3 years old. Methods involving the production or reproduction of temporal intervals have frequently encountered problems in showing temporal regulation in young children (although some other methods may fare better; see Darcheville, Rivière, & Wearden, 1993). In contrast, bisection methods produce orderly data from animal subjects (Church & DeLuty, 1977), as well as from children, young adults, and the elderly (McCormack et al., 1999; Wearden, Wearden, & Rabbitt, 1997), suggesting common timing abilities which are functional even at an early age in humans and which continue to operate well throughout the lifespan. Second, acquisition of the initial temporal discrimination between the short and long standards was more rapid in 8-year-olds than in the 3- and 5-year-olds. Third, bisection points were usually closer to the arithmetic mean of the short and long standards than the geometric mean, at least with the short/long values used in our study. Fourth, temporal sensitivity increased with age, with the 8-year-olds showing greater temporal sensitivity than the younger children.

In our study, the use of multisecond duration raises the issue of chronometric counting. Wearden, Rogers, and Thomas (1997) prevented chronometric counting during bisection with a concurrent digit-shadowing task. Such a task cannot be readily used with children, as it would probably divert their attention from the timing task itself (Arlin, 1986, 1989; Droit-Volet & Gautier, 2000). However, the use of chronometric counting to time continuous durations is less frequent in children than in adults. Three-year-old children do not count during continuous durations and although 5- and 8-year-olds can count, they do not spontaneously do so when timing (Wilkening et al., 1987). According to Wilkening et al. (1987) children up to the age of 8 evaluate duration not in quantitative but in qualitative terms. In our study, children would have been excluded from the experiment if they counted overtly, or reported in a postexperimental interview that they had counted although, in fact, none overtly employed or reported counting.

Some of our results can be compared directly with those from previous work. For example, the bisection experiment by McCormack et al. (1999) employed children of 5, 8, and 10 years of age and an undergraduate comparison group. In their study, short-duration tones (200 and 800 ms) were used as short/long standards. When just the data obtained from children in their study are considered, an age effect on the steepness of the psychophysical function was found, as in our work, but the difference was between the 5-year-olds and the two older groups, who did not differ between themselves. Bisection points obtained by McCormack et al. were almost exactly mid-way between the arithmetic (500 ms) and the geometric (400 ms) means of their short/long pair. The undergraduate group's bisection point (487.5 ms) was clearly closer to the arithmetic mean of the pair than the geometric mean (cf. Wearden, 1991).

Another comparison that might be made is between the performance of the children in our study, in terms of bisection point location and Weber ratios, and that of adults in some previous experiments. Perhaps the most direct comparison possible is with the data in Wearden, Rogers, and Thomas (1997), where young adults bisected stimulus sets with short/long values of 1/4 and 2/8 s, when counting was prevented by a concurrent digit-shadowing task. The bisection point from the 1/4-s standard pair was 2.48 s and that from the 2/8-s condition was 5.05 s, values close to most of those shown in the present Table 1. Weber ratio values were 0.17 for the 1/4-s standards and 0.18 for 2/8-s standards, when nonstandard stimuli were linearly spaced between the standards, and 0.17 and 0.15 in the 1/4-and 2/8-s conditions with logarithmic spacing of nonstandard stimuli. These values are much smaller than exhibited by the two younger groups of children in the present experiment (i.e., the adults showed higher temporal sensitivity), although values from our 8-year-olds approached those of adults. Similar Weber ratio values were reported from adults by Wearden (1991), when short/long pairs of 0.2/0.8 s (the same short/long ratio as employed in the present study) produced values of 0.20 and 0.18, in this case overlapping with Weber ratios from the 8-year-olds in the present study.

An unexpected feature of the data we obtained was the shift from arithmetic mean to geometric mean bisection in the 8-year-olds when the short/long values changed from 1 and 4 s to 2 and 8 s. Such geometric mean bisection is rarely found in adults, although it is not unknown (e.g., Allan & Gibbon, 1991; Wearden & Ferrara, 1996), and we have no ready explanation of why it occurred in our study. The theoretical models we used all accommodated this change in bisection point by changing the bias parameter, but the models offer no psychological explanation of why this should occur.

Our data and theoretical modeling support the first of the theoretical possibilities shown in Fig. 1, a change in timing sensitivity with age and, furthermore, the models attribute this developmental change to a change in the variability of the representation of short and long standards in reference memory. Although our modeling suggested that random responding may play some role in determining the slope of bisection functions in the younger children, it also showed that this is probably not the sole explanation of developmental changes and that changes in temporal memory are also implicated. The developmental change in the number of training blocks needed for mastery of the initial short/long discrimination may also point to developmental differences in the acquisition of memories of important durations. Our results may thus parallel the development of other sorts of memory in children (Cowan, 1997).

Although our study seems to clearly demonstrate changes in timing sensitivity with increasing age, what is much less clear is whether the data we obtained exhibited the scalar property of superimposition. Comparison of the present superimposition plot (Fig. 3) with that obtained from young adults by Wearden, Rogers, and Thomas (1997) from the same short/long pairs (the upper panel of their Fig. 3, p. 88) very clearly shows that the superimposition obtained from adults was better, even though, as in the present study, a between-group design was used with different groups receiving the different short/long values. On the other hand, the present Weber ratios (Table 2) offer a slightly different picture: 3-year-olds had lower Weber ratios at 2/8 s than at the shorter times, for 5-year-olds the reverse was obtained, whereas for the 8-year-olds the Weber ratios from the two different conditions were very similar. The sensitivity parameter, *c*, from the different models (Table 3) likewise failed to shed some light on whether underlying temporal sensitivity was constant when the absolute times used varied, by changing markedly between conditions, but in a way that was inconsistent for the different age groups. Overall, therefore, although our data do not directly contradict the scalar principle of superimposition by showing systematic deviation from it, they are too inconclusive to definitely support it.

Our results, analyses, and theoretical modeling join work by McCormack et al. (1999) in showing that not only can methods derived from contemporary timing theory be used successfully with children (in our case as young as 3), but also that theoretical models derived from recent work on timing in adults can provide some insight into underlying psychological processes supporting in particular the finding of McCormack et al. (1999) that there are systematic changes in timing sensitivity between younger children and those of 8 or 10 years of age. Within the framework of models like scalar timing theory, it appears that developmental changes in timing behavior are best explained by quantitative changes in processes such as reference memory rather than by fundamental qualitative changes in the way that timing is performed. If an internal clock and the related parts of the timing system proposed by contemporary timing models really exist, it seems that they are present in an intact form from an early age.

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