Journal of Experimental Child Psychology **80,** 271–288 (2001)
doi:10.1006/jecp.2001.2629, available online at http://www.idealibrary.com on IDEAL®

Temporal Generalization in 3- to 8-Year-Old Children

Sylvie Droit-Volet and Angélique Clément

Blaise Pascal University, Clermont-Ferrand, France

and

John Wearden

University of Manchester, United Kingdom

Children aged 3, 5, and 8 years were tested on temporal generalization with visual stimuli. Different groups received 4- and 8-s standards. Gradients at all ages superimposed when plotted on the same relative scale, indicating underlying scalar timing. The principal developmental changes were (i) increasing sharpness of the generalization gradient with increasing age and (ii) a change from symmetrical (3 and 5 years) to adultlike asymmetrical generalization gradients in the oldest children. Theoretical modeling attributed these changes to increasing precision of the reference memory of the standard with increasing age, as well as a decreased tendency to "misremember" the standard as being shorter than it actually was, as the children developed. © 2001 Academic Press

Key Words: children; timing; temporal perception; memory.

The past two decades have seen not only an immense growth of interest in timing processes in adult humans and animals, but also renewed interest in the development of timing processes. Block, Zakay, and Hancock (1999) and Droit-Volet (2000) provide recent reviews, pointing out the diversity of approaches used in developmental studies. However, many methods used previously in developmental studies of timing did not allow the accurate assessment of timing abilities in young children because they required the child's understanding of complex instructions and/or the ability to precisely control their motor responses, as in interval production and reproduction tasks, for example (Droit-Volet, 1998; Droit-Volet & Gautier, 2000).

Recently, two studies have adapted for children some simpler time judgment procedures originally employed with animals and later modified for adults. McCormack, Brown, Maylor, Darby, and Green (1999) and Droit-Volet and Wearden (2001) studied the temporal regulation of behavior in children from 3 to

Address correspondence and reprint requests to Sylvie Droit-Volet, Laboratoire de Psychologie Sociale de la Cognition, CNRS (UPRE-SA 6024), Université Blaise Pascal, 34 avenue Carnot, 63007 Clermont-Ferrand Cedex, France. E-mail: droit@srvpsy.univ-bpclermont.fr.

0022-0965/01 $35.00

10 years old on temporal bisection tasks with stimuli which were either short (<1 s; McCormack et al., 1999) or of longer duration (up to 8 s; Droit-Volet & Wearden, 2001). The McCormack et al. (1999) study also used a temporal generalization method with 5-, 8-, and 10-year-old children, but used only a single short temporal generalization standard duration (400 ms). The purpose of the present study was to extend the developmental study of temporal generalization to children younger than previously tested (by including 3-year-old children) and to longer stimulus durations (4 and 8 s).

In the temporal generalization task, participants are initially presented with a stimulus identified as having some standard duration (e.g., 400 ms or 4 s). Then they receive a series of comparison stimuli, which are shorter than, longer than, or equal in duration to the standard. Participants simply have to judge whether or not the just-presented comparison duration was the standard (e.g., by a YES/NO response).

The result of such a procedure is a *temporal generalization gradient*, a plot of the proportion of responses corresponding to identifications of a comparison stimulus as the standard (YES responses) against comparison stimulus duration. Temporal generalization gradients usually peak at the standard value. The proportion of identifications of a stimulus as the standard decreases progressively as its deviation from the standard duration value increases. Temporal generalization gradients from adults show a positive rightward skew in that stimuli longer than the standard are more likely to be confused with it than stimuli shorter by the same amount. For example, a 500-ms stimulus is more likely to be confused with a 400-ms standard than is a 300-ms stimulus. Such asymmetry is found in student-age adults (McCormack et al., 1999; Wearden, 1992), and the elderly (McCormack et al., 1999; Wearden, Wearden, & Rabbitt, 1997), and is also obtained when students judge longer durations (standards up to 8-s long) when counting is prevented by a secondary task (Wearden, Denovan, Fakrhi, & Haworth, 1997).

What kind of changes in temporal generalization performance might be observed in comparing children of different ages? Figure 1 shows some possibilities, which are illustrated using simulated data points derived from a computer model to be discussed in detail later. In the simulations shown, the standard duration is always 4 s, and the comparison durations range from 1 to 7 s in 1-s steps. Temporal-generalization performance in adults in such situations is characterized by asymmetrical generalization gradients which peak at the standard duration (Wearden, Denovan, et al., 1997). Another feature of the gradients obtained from adults is that the 1-s stimulus duration is hardly ever confused with the standard, indicating a high level of attention to the task and an absence of "random responding." In other words, participants are not simply making YES and NO responses with equal probability without regard to stimulus duration.

Panel a of Fig. 1 shows gradients which have the characteristics of those obtained from adults, but which differ in relative steepness. That is, in one of the gradients there is less differentiation of the stimulus durations in terms of pro-

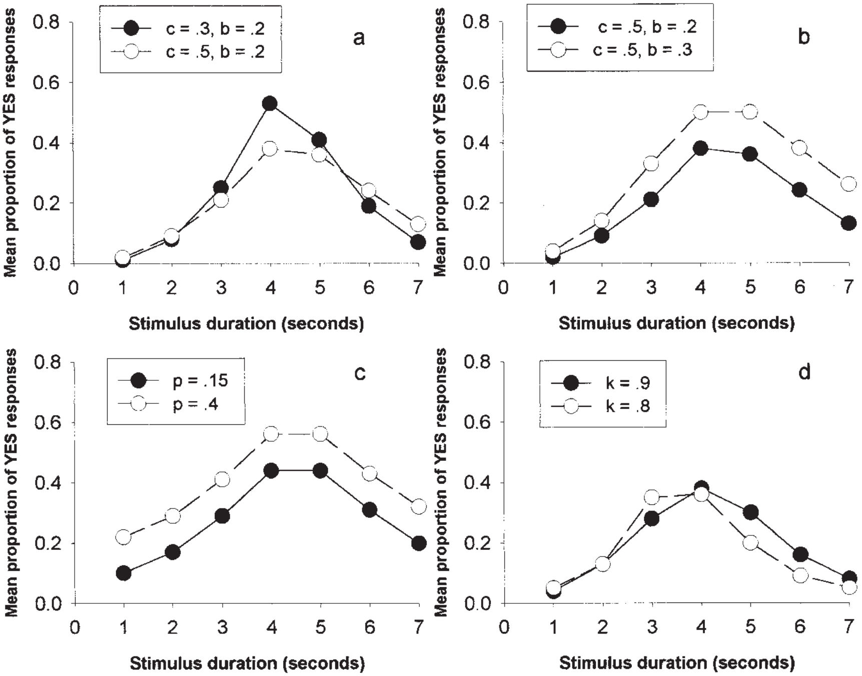

FIG. 1. Illustration of four potential developmental changes in temporal generalization gradients; see text for details. Results come from simulations using a computer model discussed in the text, and the parameter values shown in each panel come from this model.

portion of YES responses than in the other. The first developmental possibility is that gradients from children of different ages differ in steepness, but otherwise resemble those from adults. In temporal generalization studies, the relative steepness or flatness of gradients is usually attributed to different sensitivities to duration, with steeper gradients arising when temporal sensitivity is higher. An effect of this sort in children of different ages would thus indicate developmentally increasing sensitivity to duration. Later we discuss how this difference in obtained steepness of generalization gradients relates to the precision of underlying time representations.

Panel b shows another possibility. Here the gradients are adult-like, but one gradient shows a generally higher probability of YES responses at all comparison duration values than the other. This represents the second developmental possibility: that of gradients of near-identical shape in two age groups, but with different overall levels of responding. Panel c shows a similar, but subtly different, possibility. Once again, the two gradients have identical shapes and differ in overall levels of responding, but this time a high proportion of YES responses occurs at the shortest comparison stimulus duration. High levels of responding to short-duration stimuli remote from the standard are unknown in temporal generalization performance in adults (Wearden, 1992; Wearden, Denovan, et al., 1997;

Wearden, Wearden, & Rabbitt, 1997), but do occur in animals (Church & Gibbon, 1982), where they are interpreted as resulting from random responses not controlled by stimulus duration. The third developmental possibility is that some age-groups have a higher tendency than other groups to produce such random responses. Panel d shows gradients which are not the same asymmetrical shape as those obtained in adults. In the cases shown the gradients are either more or less completely symmetrical or skewed to the left, so that some stimuli shorter than the standard are more confused with it than stimuli longer by the same amount. The fourth developmental possibility is thus some systematic change in the shape of generalization gradients as children age.

The four possibilities shown in Fig. 1 are not, of course, mutually exclusive, so combinations (different gradient shapes combined with different levels of responding, for example) can occur. How the different gradient forms are generated by different parameters of theoretical models is discussed later.

Two previous developmental studies have used temporal generalization methods. In the first, Wearden, Wearden, and Rabbitt (1997) compared adults ranging in age from 60 to 69 or 70 to 79 years, with a 400-ms standard. The participants were selected so that the two age groups did not differ significantly in IQ. Comparison of gradients from the two age ranges showed results like those in panel a of Fig. 1: older people produced slightly flatter gradients, but overall gradient shapes, and overall levels of responding, were not affected by age. In the second developmental study, McCormack et al. (1999) compared the performance of 5-, 8-, and 10-year-old children on temporal generalization with a 400-ms standard duration. McCormack et al. also included a young adult group and two groups of elderly participants. In their study with children, an apparent developmental change was found in the shape of the temporal generalization gradients obtained: the gradients from their youngest children (5 years of age) were systematically skewed to the left (that is, stimuli shorter than the standard were more likely to be confused with it than stimuli longer by the same amount). However, the leftward skew decreased with increasing age toward symmetrical gradients in 10-year-olds and rightward-skewed gradients in young adults and the elderly. Furthermore, McCormack et al. observed that the temporal generalization gradient was steeper in the older children, although the oldest participant groups showed flatter gradients than did young adults (as found by Wearden, Wearden, & Rabbitt, 1997). Thus McCormack et al.'s results were a combination of the effects shown in the different panels of Fig. 1: there were developmental changes in gradient steepness (panel a), but also changes in shape (panel d).

In addition to investigating possible developmental changes in temporal generalization in children, our study was also intended to test whether their temporal generalization performance exhibited the *scalar property* of variance. The scalar property is a form of Weber's law, essentially the requirement that the standard deviation of time judgments grows as a constant fraction of the mean time judgment, as absolutely different time values are judged. There are various ways to test the scalar property in data, but one of the most commonly used is to examine the data for the property of *superimposition*. Superimposition is exhibited when data from the timing of different absolute times (e.g., different standard values in temporal generalization) superimpose when plotted on the same relative scale. For temporal generalization, the appropriate form is to plot the proportion of identifications of a comparison duration as the standard against comparison stimulus duration expressed as a proportion of the standard in force. Wearden (1992) showed that temporal generalization gradients from student participants superimposed when the standard was varied over values of 400, 500, 600, and 700 ms, and various other procedural changes were made. Likewise, Wearden, Denovan, et al. (1997) obtained superimposition in temporal generalization gradients from adults with 2-, 4-, 6-, and 8-s standards. Data from adult performance on other timing tasks also show good superimposition (Allan & Gibbon, 1991; Wearden, 1995; Wearden & Ferrara, 1996; Wearden, Rogers, & Thomas, 1997), although the scalar property is occasionally violated in data from humans, for reasons which remain at present unclear (Wearden, 1999).

Superimposition is a property required by the leading theory of animal timing, scalar timing, or scalar expectancy theory (SET), which has recently enjoyed considerable success as an explanation of timing in humans (Allan, 1998). SET proposes that the raw material for time judgments comes from a pacemaker–accumulator internal clock, but the system also involves memory and decision processes (see Wearden, 1994, for an informal introduction to SET, and Gibbon, Church, & Meck, 1984, for a more rigorous one). SET provides detailed quantitative models of performance on timing tasks by proposing specific interactions between its clock, memory, and decision stages, and a SET-based model will be presented later as an account of the data collected in the present study.

Superimposition is almost uniformly obtained in animal timing studies (e.g., Church & Gibbon, 1982), in addition to the majority of work with humans carried out within the SET framework (e.g., Rakitin et al., 1998), and is supposed to reflect the use of a common scalar timing system underlying performance on a range of tasks. It would be interesting to know whether superimposition, and hence underlying scalar timing, is present in children as young as 3. In order to test for the property of superimposition in data, participants must be tested on more than one absolute time value. This means that McCormack et al. (1999), who used just a single standard value (400 ms) in their study, could not determine whether or not superimposition occurred. Droit-Volet and Wearden's (2001) experiments on temporal bisection were used to examine superimposition in bisection, but were inconclusive in this respect: although their results did not directly contradict superimposition, even with 3-year-old children, variability in data precluded any firm positive conclusion that superimposition was present.

In summary, the experiment reported here is the first to study temporal generalization in children as young as 3 years, with long stimulus durations. Furthermore, the use of two different standard duration values allows a test of superimposition in data from children. We tested children aged 3, 5, and 8 years on temporal generalization, with different subgroups at each age given standards of 4 and 8 s.

METHOD

Participants

Ninety children from nursery and primary schools in Clermont-Ferrand, France, participated. These comprised thirty 3-year-olds (15 girls and 15 boys, $M = 3.5$ years, $SD = 0.37$), thirty 5-year-olds (13 girls and 17 boys, $M = 5.3$ years, $SD = 0.5$), and thirty 8-year-olds (15 girls and 15 boys, $M = 8.5$ years, $SD = 0.27$). Ten additional children (four 3-year-olds, four 5-year-olds, and two 8-year-olds) were excluded from the analysis because they did not produce differentiated proportions of YES responses between stimulus durations. No children adopted a behavior indicating that they were counting or reported that they counted during a post-experimental interview.

Materials

The children were tested individually in a quiet room in their school using a PowerMacintosh computer. The experimental task and data recording were controlled by Psyscope software (Cohen, McWhinney, Flatt, & Provost, 1993). Responses were made on the left (red) and right (green) buttons of a Psyscope response box, and the central (yellow) button was covered. The stimulus whose duration was varied was a 4.5-cm diameter blue filled circle presented in the center of the computer screen. Post-response feedback was given in the form of a picture of a clown who was either smiling (correct responses) or frowning (incorrect ones). The clown was presented in the center of the computer screen and was displayed for 2 s.

Procedure

Half the children in each age group were randomly assigned to one of two duration groups. For the 4-s duration group, the standard duration was 4 s and the nonstandard durations were 1, 2, 3, 5, 6, and 7 s. For the 8-s group, the standard was 8 s and the nonstandards 2, 4, 6, 10, 12, and 14 s.

The children received a single experimental session. They were initially shown the standard, appropriate for their duration group, five times. The experimenter said: “Look, it’s your circle. It stays on for a certain time.” Then, the children were told that they would see their circle among others which look like it but which stay on the screen for a shorter or a longer time. Thus, they should press on the right button if they judged that the stimulus presented was “their” circle (which we call a YES response) and on the left button if they judged that it was not “their” circle (a NO response). The order of assignment of responses to buttons was counterbalanced.

Each child was given 10 blocks of 9 trials, with each nonstandard stimulus being presented once, and the standard 3 times, with the different stimuli being presented in a random order within each block. The intertrial interval value was randomly chosen between 1 to 3 s. A correct response resulted in the appearance of the smiling clown and an incorrect response resulted in the appearance of the frowning clown.

RESULTS

A small number of children produced a relatively small proportion of YES responses to any of the stimuli presented, including the standard. We excluded from the analysis data any child whose maximum proportion of YES responses to any of the presented stimuli (not necessarily the standard) was less than 50%. This criterion led us to reject data from one 3-year-old and three 5-year-olds, both from the groups in which the standard was 8-s long.

Data Analysis

Figure 2 shows the proportion of YES responses (i.e., judgments that a presented stimulus had the same duration as the standard) plotted against stimulus duration, with panels divided by age. Inspection of data suggests that all groups produced an orderly pattern of responses with (a) the peak of the temporal generalization gradient coinciding with the standard duration and (b) the proportion of YES responses decreasing with increasing absolute duration difference between a stimulus presented and the standard. However, inspection of the data suggested that the temporal generalization gradients were flatter in the younger children than in the older ones and furthermore that there might be changes in the shape of the generalization gradients (from more or less symmetrical gradients in the younger children to gradients skewed to the right in the 8-year-olds).

An overall ANOVA tested effects of age (3, 5, or 8 years), standard duration (4 or 8 s), and duration of comparison stimulus on the proportion of YES responses. There were overall significant effects of age, $F(2, 80) = 10.09$, $p < .001$, and stimulus duration, $F(6, 480) = 68.2$, $p < .001$, but no effect of standard duration, $F(1, 80) = 0.561$. There was a significant interaction between age and stimulus duration, $F(12, 480) = 2.94$, $p < .01$, but neither of the other two-way interactions between age and standard duration or stimulus duration and standard duration were significant, $F(2, 80) = .068$ and $F(6, 480) = .167$, respectively. The interaction between age, standard duration, and stimulus length was also nonsignificant, $F(12, 480) = .792$. The significant results in the above analysis support the two suggestions derived from inspection of the results: the proportion of YES responses overall increased with age, and the shape of generalization gradients was different in the older children.

Our next analysis tested whether the temporal generalization performance of the children showed the scalar property of variance by testing superimposition. In temporal generalization, the usual way of displaying data to test superimposition is to plot the proportion of YES responses against comparison stimulus duration, where duration is expressed as a fraction of the standard value in force. Figure 3 shows these data with panels divided by age.

Inspection of the data suggests that the superimposition was excellent for the 8-year-olds and reasonable for the two younger groups in the sense that the generalization gradients from conditions with the 4- and 8-s standard did not differ systematically. The absence of any significant effect of standard duration or any

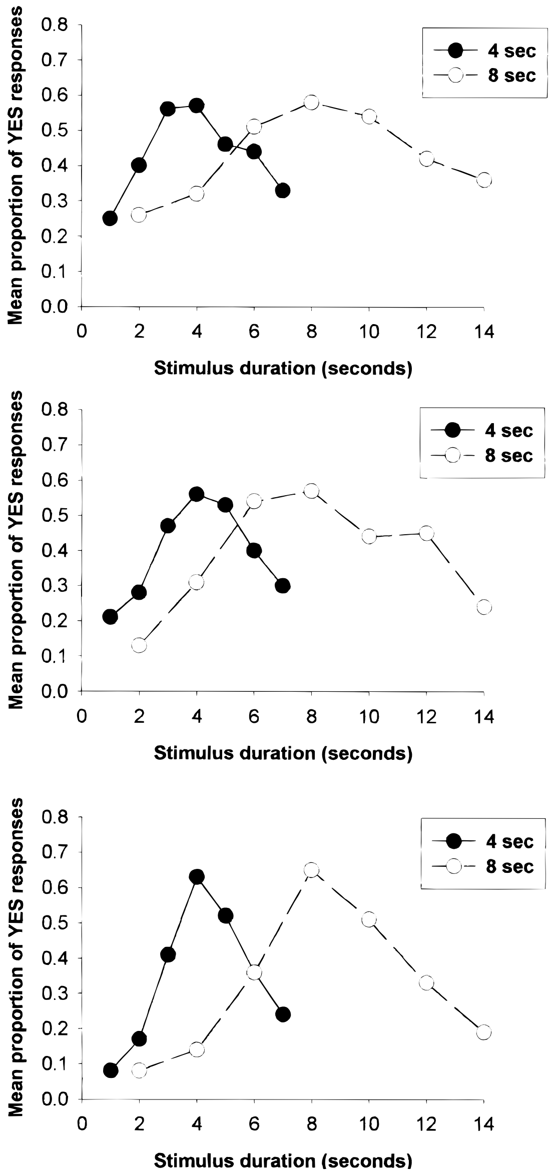

FIG. 2. Proportion of YES responses (identifications of a presented stimulus as having the standard duration) plotted against stimulus duration, for the 4-s and the 8-s duration groups. Upper panel, data from the 3-year-old group; center panel, data from the 5-year-old group; lowest panel, data from the 8-year-old group.

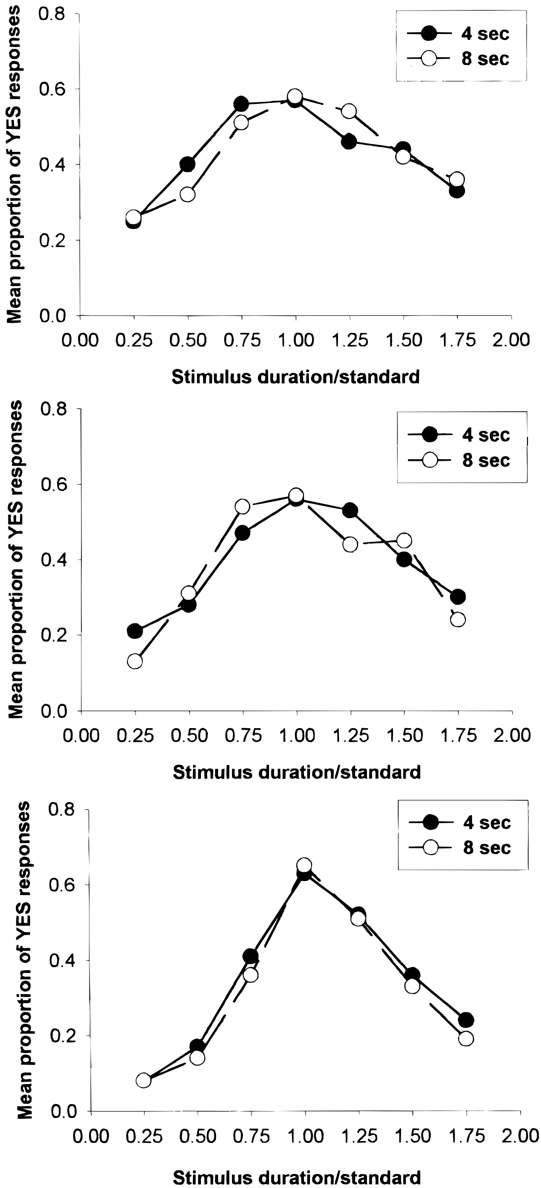

FIG. 3. Proportion of YES responses plotted against stimulus durations expressed as a fraction of the standard duration, for the 4-s and the 8-s duration groups and for each age group.

significant interaction involving this variable in the overall ANOVA presented above was consistent with superimposition, but stronger evidence comes from considering the different age-groups separately.

For the 3-year-olds, there was a significant effect of stimulus duration, $F(6, 162) = 16.99$, $p < .001$, but not of standard duration, $F(1, 27) = .064$, or standard duration by stimulus duration interaction, $F(6, 162) = .681$. The first result indicated the obvious effect that different comparison durations produced different proportions of YES responses, the second that the overall proportion of YES responses was not affected by standard duration, and the third that the generalization gradients did not differ systematically in shape. The latter two results support the suggestion that the generalization gradients from conditions with 4- and 8-s standards superimpose well.

Data from the 5-year-olds (center panel) and the 8-year-olds (lowest panel) produced identical patterns of results. Both showed significant effects of stimulus duration (5-year-olds: $F(6, 150) = 19.23$, $p < .001$; 8-year-olds: $F(6, 168) = 35.52$, $p < .001$), whereas neither age-group showed effects either of standard duration (5-year-olds: $F(1, 25) = .094$; 8-year-olds: $F(1, 28) = .586$) or of standard duration by comparison duration interaction (5-year-olds: $F(6, 150) = 1.04$; 8-year-olds: $F(6, 168) = .13$). As with the 3-year-olds, the latter two results from the older groups support the suggestion that the generalization gradients from conditions with different standard durations superimposed well. More theoretical tests of superimposition are presented later.

Inspection of the data in both Figs. 2 and 3 suggests that there might be a change with age in the shape of the generalization gradients, even though within each age-group the generalization gradients superimpose well. Gradients from 8-year-olds are apparently skewed toward the right, with more YES responses occurring to stimuli longer than the standard than to shorter stimuli. On the other hand, gradients from the younger children appear more symmetrical with unsystematic skew. Possible developmental changes in the shape of the generalization gradients were examined by testing the asymmetry of gradients around the standard duration. In the first analysis, the average proportion of YES responses to stimuli longer than the standard was compared with the average proportion to stimuli shorter than the standard by Wilcoxon tests. For the 3-year-olds there were no significant differences for either the 4- or 8-s standard ($z = -.441$ and -1.58, respectively), and the same results were obtained from 5-year-olds ($z = -1.33$ and $-.94$, respectively). On the other hand, 8-year-olds produced nearly significantly asymmetrical gradients with the 4-s standard ($z = -1.82$, $p = .07$) and significant asymmetry with the 8-s standard ($z = -2.35$, $p = .02$).

Theoretical Modeling

As noted in our introduction, SET not only predicts properties such as superimposition in behavior, but also provides quantitative models of the processes underlying tasks such as temporal generalization. Performance is derived from an interaction of internal clock, memory, and decision processes, with the latter being quantitatively specified. Specifically, Church and Gibbon (1982) proposed that their rats responded on the temporal generalization task when $\text{abs}(s^* - t)/s^* < b^*$, where s^* is a sample drawn from the reference memory of the standard s, t is the just-presented duration, and b^* is a sample drawn from a threshold, where abs indicates absolute value. More informally, the rats respond when the absolute difference between the just-presented duration and their memory of the standard, divided (or "normalized") by the standard, is "close enough" to the standard, with the close-enough decision being controlled by the threshold b^*. Such a model produces nearly symmetrical temporal generalization gradients, as discussed elsewhere (e.g., Wearden, 1994).

To model temporal generalization results from adult humans, Wearden (1992) introduced a *modified Church and Gibbon* model (MCG), which assumed that the adults responded YES when $\text{abs}(s^* - t)/t < b^*$, where all terms are as the original Church and Gibbon model, above. Note that the only difference between the two models lies in the decision rule employed. The difference between the just-presented-duration value and the standard memory sample is normalized by the standard memory sample in the Church and Gibbon model and by the duration value in the MCG model. The MCG model fits the right-skewed generalization gradients obtained from adult humans well in a number of cases (Wearden, 1992; Wearden, Denovan, et al., 1997; Wearden, Wearden, & Rabbitt, 1997).

The two upper panels of Fig. 1 illustrate some simple properties of the MCG model. In panel a, c, the coefficient of variation of the memory of the standard, s, takes two values (.5 and .3), with b constant. Increasing c (i.e., making the memory of the standard more "fuzzy") flattens the generalization gradient, but it is still the case that few YES responses occur at the shortest stimulus duration. Panel b of Fig. 1 shows the effect of varying the threshold, b, over values of .2 and .3. Increasing b makes the decision as to whether to respond YES less conservative, and the overall proportion of YES responses increases, while the general shape of the gradient, as well as the fact that few YES responses occur at 1 s, remains constant. In general, increasing c flattens the generalization gradient, while increasing b increases the overall proportion of YES responses occurring.

Inspection of the data obtained from the different age groups in our study (Fig. 2) suggests that the behavior of the 8-year-olds was in reasonable accord with the MCG model. Generalization gradients from conditions with 4- and 8-s standards were peaked at the standard and asymmetrical in the direction found in adults (right-skewed), and few YES responses occurred at the shortest durations (albeit more than in adults; cf. Wearden, Denovan, et al., 1997). However, the younger children behaved differently in two ways. First, their generalization gradients showed substantial amounts of YES responding at the shortest durations. Second, the gradients were not clearly right-skewed, being either more or less symmetrical around the standard (e.g., 3-year-olds, 8-s standard) or even slightly left-skewed (3-year-olds, 4-s standard). How can these two apparent deviations from the simple MCG model be interpreted?

The relatively high proportion of YES responses at the shortest duration tested is reminiscent of the behavior of rats in Church and Gibbon's (1982) original temporal generalization study. Exploration of the MCG model shows that although increasing *c* flattens the gradient and increasing *b* increases the overall level of responding, there are no values of these parameters that can produce 20+% YES responses at the shortest duration while at the same time simulating a gradient where the number of YES responses varies markedly with stimulus duration. Some additional factor seems to be needed, and we will employ the original idea of Church and Gibbon (1982), namely, that some proportion of the responses observed are emitted at random (i.e., YES and NO responses are emitted with equal probability without regard to stimulus duration). The effect of such a manipulation is shown in panel c of Fig. 1. To produce the simulation shown in that panel, *c* was .5, *b* was .2, and the proportion of responses emitted at random (*p*) was varied over values of .15 and .4. Obviously, increasing *p* increased the proportion of YES responses occurring at each stimulus duration, but unlike changes in the threshold, *b*, now the proportion of YES responses at the shortest stimulus duration increases markedly with increases in *p*. It seems reasonable, therefore, to attribute the high proportion of YES responses at the shortest stimulus values to random responding.

The fact that some gradients from the younger children are not right-skewed also poses problems for the simple MCG model. McCormack et al. (1999) observed similar results, with gradients from adults being right-skewed and those from children being either left-skewed or symmetrical around the standard. Their interpretation was in terms of a *distortion* value, *k*, which applied to the memory of the standard. If *k* was 1.0, the standard value was remembered veridically; if *k* was < 1.0, the standard was remembered as shorter than it really was; if *k* was $>$ 1.0 (a case not used by McCormack et al.), the standard was remembered as longer than it really was. Exploration of the MCG model with this factor added showed that when *c* was small, even small amounts of distortion (i.e., *k* just less than 1.0) produced gradients that were markedly skewed to the left. However, when *c* was larger, distortion values in the range .8 to .9 could produce near-symmetrical gradients. We therefore followed McCormack et al. (1999) in introducing this parameter into the MCG model.

The MCG model with *p* and *k* added was embodied in computer programs written in Visual Basic 6.0 (Microsoft Corporation). The standard duration *s* (4 or 8 s) was represented as a Gaussian distribution with mean *s* and coefficient of variation *c*, and on each trial a value s^* was randomly sampled from this distribution. *c* represents the variability of memory representation of *s*: larger values of *c* indicate more variable (*fuzzier*) standard memories. In the *classical* embodiment of scalar timing theory (e.g., Gibbon et al., 1984) the property of superimposition is derived from the memory of the standard duration, so in the present case, data which empirically superimpose would be expected to be modeled with simulations having identical (or at worst very similar) values of *c*. The duration to be judged (*t*) was assumed to be represented without error (i.e., as its real clock value). The threshold *b* was represented as a Gaussian distribution with mean *b* and the standard deviation was always kept constant at 0.5*b*, as previous simulations (e.g., Wearden, 1992) had shown that little was gained by varying this parameter. On each trial, a sample (*b**) was randomly chosen from the distribution of the threshold. The mean threshold value, *b*, was the second parameter of the model. In addition, on each trial there was some probability, *p*, that the model would make an equally-likely YES or NO response, without regard to stimulus duration, with *p* being the third parameter of the model. Finally, *k* were varied, which multiplied *s**, over a range of values below 1.0.

Ten thousand trials with each stimulus value judged were run, and *c*, *b*, *p*, and *k* were varied over a wide range to obtained the best-fitting simulation in terms of mean absolute deviation (MAD), the sum of the absolute deviations between the predictions of the simulation and data, divided by 7, the number of stimuli judged.

Variability from trial to trial was thus determined by variability in *s* (the *s** sample) and variability in *b* (the *b** sample).

Figure 4 shows the data points obtained in the various conditions from the 3-, 5-, and 8-year-olds (upper, center, and lowest panels, respectively), and the best-fitting lines according to the MCG model with *p* and *k* added. Parameter values for the best-fitting model are shown in Table 1. Inspection of Fig. 4 and the mean absolute deviation values in Table 1 suggests that the model fitted data well, with MAD values being close to those obtained in previous studies (e.g., Wearden, 1992; Wearden, Denovan, et al., 1997; Wearden, Wearden, & Rabbitt, 1997).

The parameter values shown in Table 1 reveal a number of developmental trends in temporal generalization performance. First, the coefficient of variation of the memory of the standard (*c*) decreased between the children of 3 and 5 years and the 8-year-olds, indicating greater precision of temporal representation in the oldest children. Second, the proportion of responses emitted at random (*p*) decreased systematically with increasing age, having the highest values in the 3-year-olds and the lowest ones in the 8-year-olds. Third, the memory distortion value (*k*) needed to fit data decreased between the 3- and 5-year-olds and the 8-year-olds, suggesting that the younger children *misremember* the standard duration as being shorter than it really was to a greater extent that the older ones. A final weak trend that might be noted, although it was less clear than the others, is that the threshold for making the YES response (*b*) showed a slight increase with increasing age; i.e., the older children were slightly less conservative than the younger ones.

Comparison of the parameter values needed to fit data from 4- and 8-s standard conditions within each age group shows that broadly similar values of *c*, *b*, and *k* were needed to fit data from the two conditions, but there was also a suggestion that in the data from the 3- and 5-year-olds, there was a smaller proportion of random responses at the longer standard value.

DISCUSSION

Our experiments have illustrated that the temporal generalization method can yield orderly data from children as young as 3 years of age, using stimulus dura-

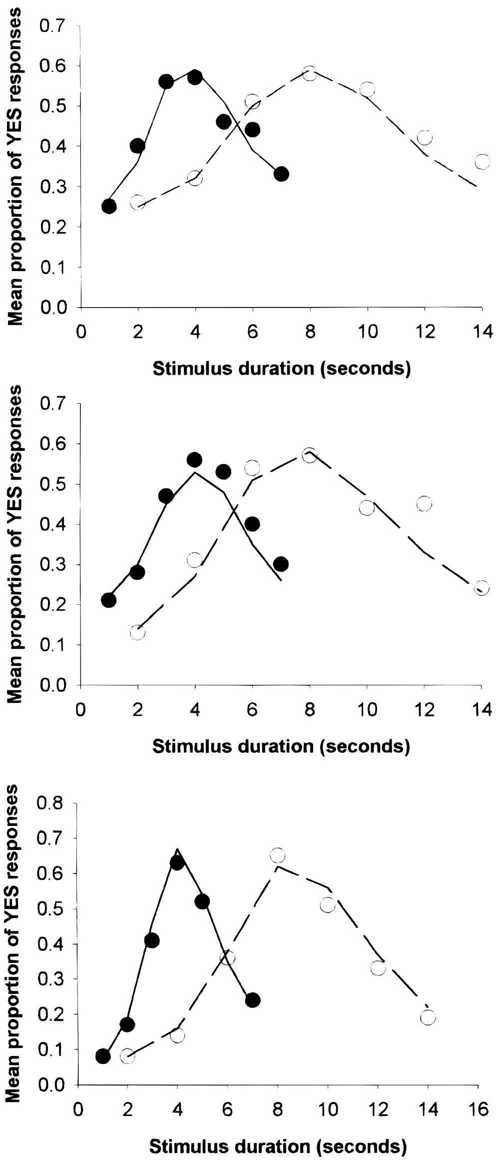

FIG. 4. Data points (unconnected filled and open circles) and fits derived from the theoretical model discussed in the text (solid and dashed lines). Upper panel, data from 3-year-olds; center panel, data from 5-year-olds; lowest panel, data from 8-year-olds.

TABLE 1
Parameter Values from Modified Church and Gibbon Model with Random Responding and Standard Memory Distortion

Age	Standard (s)	*c*	*b*	*p*	*k*	MAD
3	4	.59	.19	.52	.83	.03
	8	.53	.22	.39	.88	.02
5	4	.55	.19	.36	.90	.03
	8	.57	.27	.22	.83	.03
8	4	.35	.29	.12	.90	.02
	8	.36	.26	.12	1.0	.02

Note. The model parameters are: *c*, coefficient of variation of the memory representation of the standard; *b*, mean threshold value; *p*, probability of random responding on each trial; *k*, standard memory distortion value. The standard deviation of the threshold was always *b*/2. Also shown is mean absolute deviation (MAD).

tions 10 or more times as long as those used with children by McCormack et al. (1999). A novel feature of our results is the demonstration of superimposition, suggesting that the timing mechanism underlying timing in children is scalar in nature. Superimposition was demonstrated empirically in our data by the plot shown in Fig. 3, which indicates that the temporal generalization gradients of children of different ages approximately superimpose when the standard duration is varied. This result was consistent with the systematic lack of any significant effect of standard duration, when other factors (such as age of children or comparison stimulus duration) all produced significant effects. At the theoretical level, superimposition was indicated by the similarity of coefficient of memory of standard values (*c* in Table 1) obtained from the fits of models to the temporal generalization gradients. Within an age-group, the *c* values needed to fit data hardly changed as the standard duration varied between 4 and 8 s. These different operations all produce findings consistent with the contention that temporal generalization in children even as young as 3 years is based on a scalar timing mechanism, as is the temporal generalization performance of adults when they time durations less than 1 s (Wearden, 1992) or multisecond durations when chronometric counting is prevented (Wearden, Denovan, et al., 1997).

Our study also suggests (as does the work of Droit-Volet & Wearden, 2001) that the timing behavior of the youngest children (3 and 5 years in their work) is contaminated by random responses, that is, responses that take no account of the duration of the stimuli presented. In older children, such random responding plays a lesser role, with behavior being controlled essentially by decisions about duration, as in adults. Droit-Volet and Wearden (2001) modeled temporal bisection performance in children of 3, 5, and 8 years and found that more than 10% of trials in the younger children appeared to be random, whereas data from the 8-year-olds could be modeled with near-zero random responses. In general, the proportion of random responses needed to model data in the present study was higher, possibly indicating that the temporal generalization task is more difficult than bisection. Some supporting evidence for this comes from Wearden, Wearden, and Rabbitt (1997), who found effects of both age and general intelligence on temporal generalization in a group of elderly people, but no effect of either variable on bisection performance. Their performance was, furthermore, very close to that observed in university students about 50 years younger than the elderly participants used.

Our present study joins two other recent articles (Droit-Volet & Wearden, 2001; McCormack et al., 1999) in showing that the variability of representation of "standard" durations employed in temporal generalization and bisection tasks decreases with age. Our 8-year-olds had steeper temporal generalization gradients than the younger children (Fig. 2), and the memory variance parameter of the models fitted also declined between the ages of 5 and 8 years. In Droit-Volet and Wearden (2001) the memory variance parameter needed to model bisection performance was, as in the present study, markedly lower at 8 years than in the younger children they tested.

In McCormack et al.'s (1999) study, a different model was used, but this nevertheless incorporated a noise parameter much like our standard memory coefficient of variation, *c*. The value of this parameter systematically declined across ages of 5, 8, and 10 years, in both temporal generalization and bisection, consistent with the results of the simulations reported here. This whole body of work, using different procedures and different time ranges, clearly points to a consistent developmental trend in timing behavior involving a decrease with age in variability of the memory of standard durations which are the basis of the various time judgments made.

The development of memory for duration has not, however, been extensively studied (Droit-Volet & Rattat, 1999), which means that it is not possible to identify precisely the cause of the change in variability of standard duration representation noted in our study and that of McCormack et al. (1999). In general, however, studies of the general development of memory in children suggest that changes in performance on memory tasks might be better explained by changes in working memory rather by changes in long-term memory (Cowan, 1997). According to this position, the higher variability in the younger children's reference memory found in our study might be produced because of children's difficulties in directing and maintaining attention to time (Block et al., 1999; Droit-Volet & Gautier, 2000; Gautier & Droit-Volet, in press). On the other hand, other studies point to difficulties experienced by younger children in maintaining long-term memory representations of durations, as evidenced by effects of interfering manipulations on temporal discrimination in children (Rattat & Droit-Volet, in press). More research is needed before the cause of the apparent developmental changes in reference memory variability on timing tasks can be identified with certainty.

Another developmental trend noted in our work was a shift from symmetrical or slightly left-skewed gradients in the 3- and 5-year-olds to adult-like right-skewed gradients in the 8-year-olds. McCormack et al. (1999) found rather similar changes in gradient asymmetry in their own study. Gradients from their 5- and 8-year-old children were significantly skewed to the left, the gradient from their

10-year-olds was approximately symmetrical, and their young adult comparison group, as well as two groups of elderly participants, showed the usual rightward skew found previously (and found in 8-year-olds in the present study). McCormack et al.'s model of data from the 8- and 10-year-olds in their study required little distortion ($k = 0.96$ in both cases), but the value needed to model data from their 5-year-olds was 0.87, indicating substantial misremembering of the standard duration and in fact a distortion value similar to the ones used in our model for 3- and 5-year-old children.

Overall, the present study, Droit-Volet and Wearden (2001), and McCormack et al. (1999) together use methods and theory related to contemporary timing models such as SET to begin to elucidate how the timing processes used by children on simple timing tasks change with increasing age. The progress made with developmental versions of models of timing in adults suggests that timing processes in children have many essential features in common with timing in adults (and, indeed, with animal timing). Future research will be directed toward explaining the specific differences between timing processes in adults and children, such as the apparent misremembering of standard durations, and the higher variability with which these are represented.

REFERENCES

Allan, L. G. (1998). The influence of the scalar timing model on human timing research. *Behavioural Processes*, **44,** 101–117.

Allan, L. G., & Gibbon, J. (1991). Human bisection at the geometric mean. *Learning and Motivation*, **22,** 39–58.

Block, R. A., Zakay, D., & Hancock, P. A. (1999). Developmental changes in human duration judgments: a meta-analytic review. *Developmental Review*, **19,** 183–211.

Church, R. M., & Gibbon, J. (1982). Temporal generalization. *Journal of Experimental Psychology: Animal Behavior Processes*, **8,** 165–186.

Cohen, J., MacWhinney, B., Flatt, M., & Provost, J. (1993). PsyScope: An interactive graphic system for designing and controlling experiments in the psychology laboratory using Macintosh computers. *Behavior Research Methods, Instruments & Computers*, **25,** 257–271.

Cowan, N. (1997). The development of working memory. In N. Cowan (Ed.), *The development of memory in childhood* (pp. 163–199). Hove: Erlbaum.

Droit-Volet, S. (1998). Adaptation to time in young children: An initial force rule governing temporal behavior. *Journal of Experimental Child Psychology*, **68,** 236–249.

Droit-Volet, S. (2000). L'estimation du temps: Perspective developpmentale. *L'Année Psychologique*, **100,** 443–464.

Droit-Volet, S., & Gautier, T. (2000). Time estimation in 3- and 5 1/2-year-old children as a function of instructions and type of response. *Current Psychology of Cognition*, **19,** 263–276.

Droit-Volet, S., & Rattat, A. C. (1999). Are time and action dissociated in young children's time estimation? *Cognitive Development*, **14,** 573–595.

Droit-Volet, S., & Wearden, J. H. (2001). Temporal bisection in children. *Journal of Experimental Child Psychology*, **80,** 142–159.

Gautier, T., & Droit-Volet, S. (in press). Attentional distraction and time perception in children. *International Journal of Psychology*.

Gibbon, J., Church, R. M., & Meck, W. (1984). Scalar timing in memory. In J. Gibbon & L. Allan (Eds.), *Annals of the New York Academy of Sciences: Vol. 423. Timing and time perception* (pp. 52–77). New York: New York Academy of Sciences.

McCormack, T., Brown, G. D. A., Maylor, E. A., Darby, A., & Green, D. (1999). Developmental changes in time estimation: Comparing childhood and old age. *Developmental Psychology*, **35,** 1143–1155.

Rakitin, B. C., Gibbon, J., Penney, T. B., Malapani, C., Hinton, S. C., & Meck, W. H. (1998). Scalar expectancy theory and peak-interval timing in humans. *Journal of Experimental Psychology: Animal Behavior Processes*, **24,** 15–33.

Rattat, A.-C., & Droit-Volet, S. (in press). *Variability in 5- and 8-year-olds' memory for duration: An interfering task in temporal bisection*. *Behavorial Processes*.

Wearden, J. H. (1992). Temporal generalization in humans. *Journal of Experimental Psychology: Animal Behavior Processes*, **18,** 134–144.

Wearden, J. H. (1994). Prescriptions for models of biopsychological time. In M. Oaksford & G. Brown (Eds.), *Neurodynamics and psychology* (pp. 215–236). London: Academic Press.

Wearden, J. H. (1995). Categorical scaling of stimulus duration by humans. *Journal of Experimental Psychology: Animal Behavior Processes*, **21,** 318–330.

Wearden, J. H. (1999). "Beyond the fields we know . . .": Exploring and developing scalar timing theory. *Behavioural Processes*, **45,** 3–21.

Wearden, J. H., Denovan, L., Fakhri, M., & Haworth, R. (1997). Scalar timing in temporal generalization in humans with longer stimulus durations. *Journal of Experimental Psychology: Animal Behavior Processes*, **23,** 502–511.

Wearden, J. H., & Ferrara, A. (1996). Stimulus range effects in temporal bisection by humans. *Quarterly Journal of Experimental Psychology*, **49B,** 24–44.

Wearden, J. H., Rogers, P., & Thomas, R. (1997). Temporal bisection in humans with longer stimulus durations. *Quarterly Journal of Experimental Psychology*, **50B,** 79–94.

Wearden, J. H., Wearden, A. J., & Rabbitt, P. (1997). Age and IQ effects on stimulus and response timing. *Journal of Experimental Psychology: Human Perception and Performance*, **23,** 962–979.

Received July 3, 2000; revised November 29, 2000; published online May 29, 2001