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Speeding up an internal clock in children? Effects of visual flicker on subjective duration

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Children of 3, 5, and 8 years of age were trained on a temporal bisection task where visual stimuli in the form of blue circles of 200 and 800 ms or 400 and 1600 ms duration, preceded by a 5-s white circle, served as the short and long standards. Following discrimination training between the standards, stimuli in the ranges 200–800 ms or 400–1600 ms were presented with the white circle either constant or flickering. Relative to the constant white circle, the flicker (1) increased the proportion of "long" responses (responses appropriate to the long standard), (2) shifted the psychophysical functions to the left, (3) decreased bisection point values, at all ages, and (4) did not systematically affect measures of temporal sensitivity, such as difference limen and Weber ratio. The results were consistent with the idea that the repetitive flicker had increased the speed of the pacemaker of an internal clock in children as young as 3 years. The "pacemaker speed" interpretation of the results was further strengthened by a greater effect of flicker in the 400/1600-ms condition than in the 200/800-ms condition.

In the last decade and a half, the application to time perception in human adults of the leading theory of animal timing, scalar timing theory (SET: Gibbon, Church, & Meck, 1984), and the use of methods related to this theory, such as temporal generalization (Church & Gibbon, 1982; Wearden, 1992) and temporal bisection (Church & DeLuty, 1977; Wearden, 1991), has led to major advances in understanding many aspects of human timing (for a general review, see Allan, 1998). More recently, SET and its associated methods have been used to study timing within a developmental perspective, using both elderly people (McCormack, Brown, Maylor, Darby, & Green, 1999; Wearden, Wearden, & Rabbitt, 1997) and children (Droit-Volet, in press; Droit-Volet & Wearden, 2001; Gautier & Droit-Volet, 2002; McCormack et al., 1999; Rattat & Droit-Volet, 2001).

McCormack et al. (1999) studied temporal generalization and bisection in children of 5, 8, and 10 years of age, and Droit-Volet and Wearden (2001) and Droit-Volet, Clément, and Wearden (2001) extended the age range of children studied down to 3 years using temporal bisection and generalization methods, respectively. Children as young as 3 years showed good

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temporal regulation of behaviour, with data conforming reasonably well to principles of SET such as superimposition, the requirement that measures of timed behaviour superimpose when plotted on the same relative scale (discussed further later in this article), and modifications of SET-compatible models fitted data well. There are a number of developmental trends present in data from these sorts of experiment (some of which are replicated in the present work), and these are discussed in detail elsewhere (Droit-Volet, 2000; Gautier & Droit-Volet, 2002; McCormack et al., 1999; Rattat & Droit-Volet, 2001). The present article is focused, not on developmental trends, but on the possibility that even young children might show evidence that they possess an "internal clock".

The success of SET as an explanation of some aspects of timing in adults and children has led to a resurgence of interest in the idea that humans might possess some sort of internal clock, which has been present in the psychological literature for most of the last century (François, 1927). SET proposes that the raw material for time judgements comes from a pacemaker-accumulator internal clock, although the SET system also involves memory and decision processes. Some evidence for such an internal clock comes from studies using methods intended to "speed up" or "slow down" the pacemaker of the proposed clock. Research on the effects of body temperature on time judgements in humans (for a review, see Wearden & Penton-Voak, 1995) was part of this effort, as were some well-known studies of the effects of drugs on timing in animals, such as those of Maricq, Roberts, and Church (1981) and Meck (1983).

More recently, a method invented by Treisman and colleagues (Treisman, Cook, Naish, & MacCrone, 1994; Treisman, Faulkner, & Naish, 1992; Treisman, Faulkner, Naish, & Brogan,1990) has been used to apparently alter pacemaker speed in humans. Treisman and colleagues proposed that accompanying or preceding an event to be timed by a short period of repetitive stimulation (clicks or flashes) had two effects. One was an increase in pacemaker speed; the other was interference with timing processes at certain specific frequencies of stimulation. However, the former effect has received more subsequent attention than the latter (although see Burle & Bonnet, 1997, 1999). In recent studies, changes in subjective time occasioned by repetitive periodic clicks have been obtained by Penton-Voak, Edwards, Percival, and Wearden (1996), Wearden, Edwards, Fakhri, and Percival (1998), and Wearden, Philpott, and Win (1999), as well as by Burle and Bonnet (1997, 1999) and Burle and Casini (2001). These authors used different experimental paradigms involving, for example, the timing of auditory and visual stimuli in various conditions and the production of timed responses. In general, clicks made stimuli seem to last longer than before, whereas response durations produced were shortened by the click manipulation; exactly the effects predicted by an increase in pacemaker speed.

Although there seems little doubt that repetitive stimulation preceding timed events can affect subjective duration, pacemaker speed changes are not the only possible explanation for the effect found (Penton-Voak et al., 1996). As discussed later, other aspects of the internal clock might be affected or, alternatively, some other parts of the timing system, such as decision processes, might be implicated. Further information on the scope of repetitive stimulation effects on timing would be useful, and the present article seeks to provide some by examining the effects of repetitive stimulation (in the form of flicker) on timing of visual stimuli by children of 3, 5, and 8 years of age.

The main focus of interest of the present study is on the effect of flicker on judgements of subjective duration in children assessed by a temporal bisection method. Obtaining a "speeding up the clock" effect of flicker in children of different ages would support the view that the mechanism of operation of repetitive stimulation is a very direct and fundamental one, possibly simply changing how long the stimuli presented seem to last in a manner compatible with the original suggestion of Treisman et al. (1990) that pacemaker speed is increased.

In addition to investigating possible pacemaker speed changes in children, the present article also addresses other issues. The most important of these is whether behaviour on the bisection task used conforms to one of the main requirements of SET, the *scalar property* of variance, which gives the theory its name. The scalar property is the requirement that the standard deviation of time judgements varies as a constant fraction of the mean judgement, as the durations timed change, a form of conformity to Weber's law. In psychological terms, this means that the timing system behaves as if it has constant sensitivity, regardless of the absolute values of the intervals timed. One prediction of SET is that Weber-fraction-like measures of behaviour (like the Weber ratio to be discussed later) should remain constant as the range of intervals timed varies, and we provide a test of this in our study.

A particularly powerful form of the scalar property is *superimposition*, the requirement that measures of timed behaviour remain invariant when plotted on the same relative scale (e.g., when all absolute durations are plotted as fractions of some standard, which reflects the durations in force in the conditions tested). To evaluate the scalar property, either by examination of Weber ratios or by superimposition, more than one time range must be studied, so McCormack et al.'s (1999) experiment on bisection in children, which used just a single set of time values for each task, could not test whether the scalar property was present in children's behaviour. The present study uses two duration ranges to enable the superimposition property, as well as constancy of Weber ratios, to be tested. For further discussion of superimposition in timing behaviour in children see Droit-Volet and Wearden (2001) and Droit-Volet et al. (2001). The question of how the scalar property might be derived more generally is discussed in some detail by Wearden and Bray (2001).

In most studies of temporal bisection in humans, people are initially presented with two stimulus durations, one identified as a "short" standard (S), the other identified as a "long" standard (L). In the case of young children, some training may be needed before S and L are reliably discriminated (Droit-Volet & Wearden, 2001, and the present study), but in adults the training phase may just consist of a few presentations of S and L (Wearden, 1991). After learning S and L, humans are presented with a range of stimulus durations (S and L, as well as intermediate values) and are required to classify each duration in terms of its similarity to S or L. The measure of behaviour usually taken is the proportion of responses appropriate to L ("long" responses) as a function of presented stimulus duration. The psychophysical function relating the proportion of "long" responses to stimulus duration is usually an ogive-shaped curve, at least in adults, which ranges from near-zero "long" responses when the stimulus that is actually S is presented, to near-100% when L is presented.

The psychophysical function can be analysed to yield a number of measures of timing behaviour. The most commonly used is the bisection point, the stimulus duration giving rise to 50% "long" responses, and considerable interest has focused on issues such as where the bisection point is located as a function of S and L (e.g., at the arithmetic mean of S and L, the geometric mean, or elsewhere: see Allan & Gibbon, 1991; Wearden, 1991; Wearden & Ferrara, 1995, 1996; Wearden, Rogers, & Thomas, 1997, for discussion). Previous studies with children have found that the bisection point was located close to the arithmetic mean of S and L

(Droit-Volet & Wearden, 2001; McCormack et al., 1999; Rattat & Droit-Volet, 2001), the usual result obtained with adults.

To test superimposition in bisection, the appropriate method is to plot the proportion of "long" responses produced at each stimulus duration against stimulus duration divided by the bisection point for the condition plotted (Allan & Gibbon, 1991). When this is done, data from adults superimpose well (Allan & Gibbon, 1991; Wearden, Rogers et al., 1997), at least if the *S*/*L* range is kept constant (e.g., at 1/4: see Ferrara, Lejeune, & Wearden, 1997, for discussion). Droit-Volet and Wearden (2001) tested superimposition in children of 3, 5, and 8 years of age when *S*/*L* values were 1/4 s and 2/8 s. Data from the oldest group superimposed well, but those from the younger children were ambiguous (although they did not deviate markedly from superimposition). On the other hand, Droit-Volet et al. (2001) found good superimposition in children as young as 3 years when temporal generalization with 4- and 8-s standards were used.

Children up to 8 years of age do not spontaneously use chronometric counting when multi-second durations are used (Wilkening, Levin, & Druyan, 1987), which means that studies of non-counting-based timing can employ longer durations without needing a secondary task to suppress counting (as had to be used in a study of longer duration bisection in adults by Wearden, Rogers et al., 1997, for example). In the present study, however, we followed McCormack et al. (1999) and used shorter durations, *S*/*L* pairs of 200/800 ms and 400/1600 ms. Shorter durations have the advantage that the experimental trials and sessions are considerably shorter than those when multi-second durations are employed, so children may find it easier to maintain attention to the task.

In the experiment here, children in three age groups (3, 5, and 8 years) were initially trained to discriminate two durations (*S* and *L* standards of either 200 and 800 ms, or 400 and 1600 ms, depending on condition), presented in the form of blue circles, which were preceded by a constant duration, non-flickering, white circle. Following training with the appropriate standards, the children were tested with other blue circles, whose durations of presentation ranged from *S* to *L*. After presentation of each stimulus, the child made one response to classify the stimulus as more similar to *S* than to *L*, and another response (the "long" response) if it seemed more similar to *L*. In different testing conditions, the blue circles were preceded either by a 5-s-duration non-flickering white circle, or by a 5-s-duration white circle that flickered at 7 Hz. If the visual flicker increased subjective duration, then the subsequently presented blue circle would be expected to have greater subjective duration after flicker than without flicker, and thus a tendency to give rise to more "long" responses. A second result that might also be obtained is a displacement of the psychophysical function towards the left, accompanied by shortening in bisection point values. Such effects would be prima facie evidence for a change in subjective time in children as a result of repetitive stimulation. How to distinguish pacemaker speed change interpretations of such an effect from others is discussed further later.

Method

Subjects

The sample used to provide data in the present study consisted of 38 children: nine 3-year-olds (6 girls and 3 boys, mean age = 3.5 years, *SD* = 0.41), eleven 5-year-olds (6 girls and 5 boys, mean age = 5.4 years, *SD* = 0.38), and eighteen 8-year-olds (8 girls and 10 boys, mean age = 8.2 years, *SD* = 0.20). There were 17 additional children tested (nine 3-year-olds and eight 5-year-olds), but they were excluded from the final sample because in each duration condition (200/800 ms and 400/1600 ms) they did not produce clearly differentiated proportions of "long" responses. All children came from nursery and primary schools in Clermont-Ferrand, France.

Materials and apparatus

The children were tested individually in a quiet room in their schools. A Power Macintosh computer controlled experimental events and recorded data with Psyscope (Cohen, MacWhinney, Flatt, & Provost, 1993). Responses were made on the right and the left buttons of a Psyscope response box. The stimuli used for the bisection task were a blue circle and a white circle, both 4.5 cm in diameter, which were presented in the centre of the monitor screen. During the training phase, post-response feedback was a picture of a clown who was either smiling (after correct responses) or frowning (after incorrect ones). The clown picture was presented for 2 s in the centre of the monitor screen.

Procedure

Each child was assigned to two duration bisection conditions, a 200/800-ms-duration condition and a 400/1600-ms-duration condition, with condition order counterbalanced. In the 200/800-ms condition, the target stimulus (the blue circle) was 200 ms for *S* and 800 ms for *L*, and the durations between *S* and *L* presented during the test phase were 300, 400, 500, 600, and 700 ms. In the 400/1600-ms condition, *S* and *L* were 400 ms and 1600 ms, and intermediate test durations were 600, 800, 1000, 1200, and 1400 ms.

For each duration condition, the children received three successive phases: pretraining, training, and testing. In pretraining, the child was shown *S* and *L* (in the form of a blue circle), with each standard being presented five times in alternation. In the pretraining phase, as well as in the training and the testing phases, the stimulus whose duration was to be classified was always a blue circle and was always preceded by a white circle, which was displayed for 5 s. The instructions given by the experimenter for the *S* and *L* were "look at this white circle . . . look at this blue circle . . . This blue circle is the short/long circle. It stays on for a short/long time".

During the training phase, the child was trained to press one button on the response box after *S* and the other button after *L*. The association of *S* and *L* with the left and the right buttons was counterbalanced. Each child was given successive blocks of eight trials, and *S* and *L* had a 50% probability of appearance on each trial, with an intertrial interval value randomly chosen between 1 and 3 s. A correct response resulted in the appearance of a smiling clown and an incorrect response the appearance of the frowning clown and the 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.

After a successful training block, the child was given the testing phase. This 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". Then, she added, "Sometimes, the white circle will flicker, sometimes it won't, but don't pay attention to its flickering. Look carefully at the white circle that flickers or not, and then look also carefully at the blue circle." Each child received eight blocks of 14 trials: on 7 trials the white circle that preceded the blue circle (whose duration was the basis of the response) flickered, and on 7 trials the white circle was constant. A flicker frequency of 7 Hz was used for all flicker trials in both duration conditions. The 7 trials, with or without flicker, consisted of the presentation of *S* and *L*, as well as the five intermediate durations. The 14 trials within each block were presented in a random order.

Results

Table 1 shows the number of children in each age group requiring different number of training blocks to meet the learning criterion (eight consecutive correct responses) for the 200/800-ms and the 400/1600-ms conditions. A Kruskal–Wallis test showed that the number of blocks required varied significantly with age, $\chi^2(2) = 31.35$, $p < .001$. Between-age comparisons found significant differences between each age group, between the 3- and the 5-year-olds (3.17 vs. 1.5 blocks, Kolmogorov–Smirnov, $Z = 2.02$, $p < .01$), as well as between the 5- and the 8-year-olds (1.5 vs. 1.0, $Z = 1.66$, $p < .01$). In addition, the 3-year-olds required more training blocks in the 200/800-ms condition than in the 400/1600-ms condition (3.56 vs. 2.78, $Z = 2.65$, $p < .01$, by Wilcoxon test), although the effect of duration condition order was not significant. In contrast, for both the 5- and the 8-year-olds, the number of blocks required to meet the learning criterion did not significantly differ in the two duration conditions. These results suggest that learning to differentiate the short standard from the long standard required more training in the 3-year-olds than in the older children, especially when the S/L values were 200 and 800 ms.

Figure 1 shows the mean proportion of "long" responses during the testing phase, plotted against stimulus duration as a function of the flicker condition (no flicker and flicker, NF and F in Figure 1) for the two duration ranges (200/800 ms and 400/1600 ms). The top panel shows data from the 3-year-olds, the centre panel data from the 5-year-olds, and the lowest panel data from the 8-year-olds. Inspection of psychophysical functions suggests that the proportion of "long" responses increased as a function of the stimulus duration in all three age groups and for both duration ranges. However, it suggests also that there was an effect of age on the steepness of their slopes, with the oldest children producing psychophysical functions that increased more abruptly with increasing stimulus duration. In spite of this age-related change in the slope of psychophysical functions, whatever the age of children tested, the psychophysical functions appeared to be systematically shifted to the left in the flicker condition compared to the no-flicker condition, at both the 200/800-ms and 400/1600-ms duration ranges. These suggestions were supported by subsequent statistical analyses.

TABLE 1

Number of children requiring different numbers of training blocks to meet the learning criterion[a] for the different age groups and for the two different duration ranges

		Number of blocks required			
Age group	*Duration range*[b]	*1*	*2*	*3*	*4*
3-year-olds	200/800	0	0	4	5
	400/1600	0	2	7	0
5-year-olds	200/800	7	2	2	0
	400/1600	6	5	0	0
8-year-olds	200/800	18	0	0	0
	400/1600	18	0	0	0

[a] 8 consecutive correct responses to S and L.

[b] In ms.

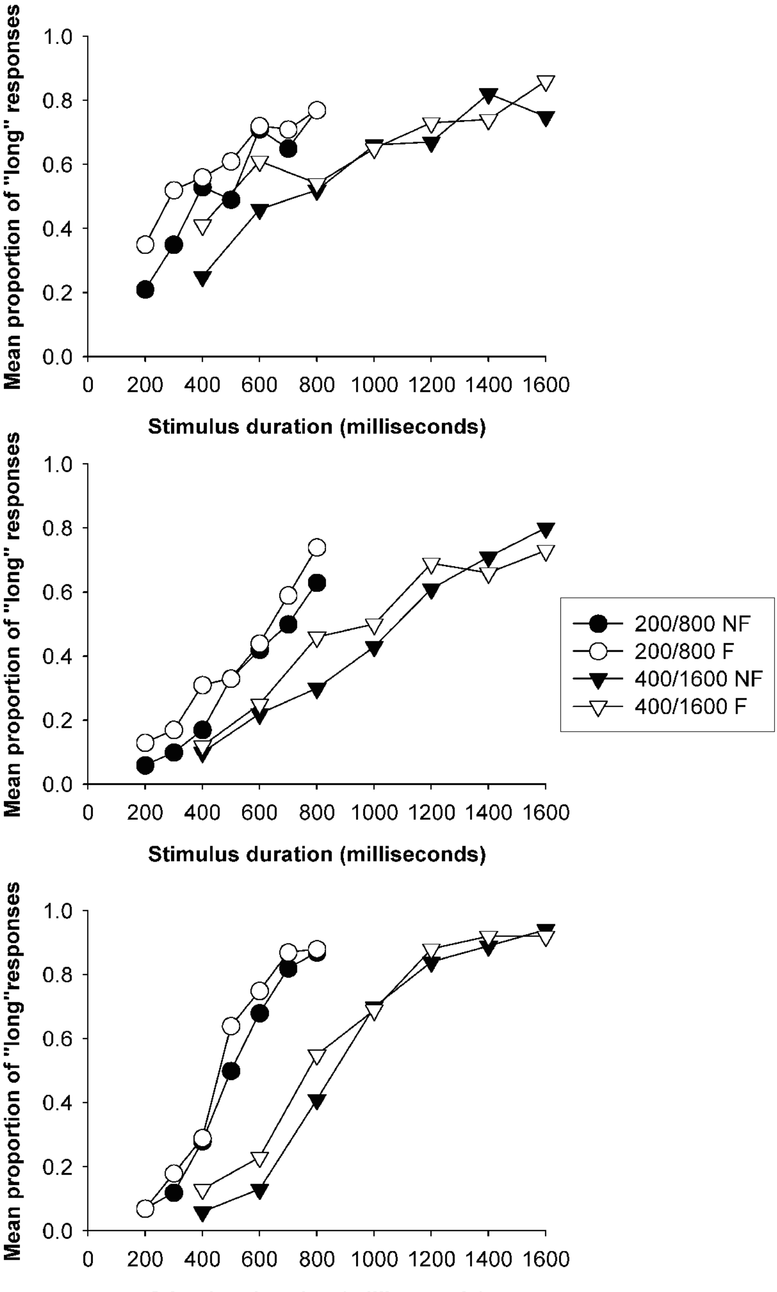

Figure 1. Proportion of "long" responses (proportion of judgements that a presented stimulus was more similar to the "long" standard than to the "short" one), plotted against stimulus duration. Data are shown separately for the 200/800 ms and the 400/1600-ms conditions, with and without flicker (F and NF). Top panel: data from 3-year-olds; centre panel: data from 5-year-olds; lowest panel: data from 8-year-olds.

An overall analysis of variance (ANOVA) examined effects of age (3, 5, or 8 years), stimulus duration, duration range (200/800 ms or 400/1600 ms), and flicker condition (flicker or no flicker) on proportion of "long" responses. A previous ANOVA had found no significant effects of sex, button assignment, and duration condition order, nor any significant interactions between these procedural variables and the main experimental variables of the study (age, etc.), so data were collapsed across the procedural factors. There were significant effects of age, $F(2, 35) = 20.05, p < .0001$, stimulus duration, $F(6, 210) = 283.23, p < .0001$, duration range, $F(1, 35) = 12.24, p < .001$, and presence or absence of flicker, $F(1, 35) = 35.22, p < .0001$. No interaction involving flicker presence/absence was significant, however. There was also a significant interaction between age and stimulus duration, $F(12, 210) = 16.41, p < .001$. The Stimulus Duration × Duration Range, and Age × Stimulus Duration × Duration Range interactions were not significant.

Of the effects noted, perhaps the most interesting was the effect of flicker, which significantly increased the proportion of "long" responses overall, but did not interact with age. That is, the effect of flicker appeared independent of the age of the subjects tested. Other age effects could be noted, however, as are discussed later.

We next analysed the overall pattern of results more finely by examining data from each age group separately. For the 3-year-olds, there was a significant effect of flicker, $F(1, 8) = 6.22$, $p < .04$, but neither two- nor three-way interactions between the flicker and other factors (stimulus duration and duration range) were significant. This pattern of results shows that children as young as 3 years of age made more "long" responses in the flicker condition than in the no-flicker condition—that is, the subjective duration of the stimuli presented was apparently increased by the flicker. There was also a significant effect of stimulus duration, $F(6, 48) = 31.27, p < .001$ (i.e., the different stimulus durations produced different proportions of "long" responses), but not of duration range, nor a significant Stimulus Duration × Duration Range interaction. The first of these non-significant results shows that the duration range did not affect the proportion of "long" responses; the second that the psychophysical functions at the different duration ranges did not differ in shape.

Data from the 5-year-olds produced a similar pattern of results. There were significant effects of flicker, $F(1, 10) = 18.81, p < .001$, and stimulus duration, $F(6, 60) = 93.85, p < .01$, but no significant effect of duration range. In addition, none of the two- or three-way interactions involving flicker and/or duration range was significant.

In the 8-year-olds, the effects of flicker, $F(1, 17) = 17.82, p < .01$, and stimulus duration, $F(6, 102) = 272.57, p < .01$, were significant, as was the effect of duration range, $F(1, 17) = 12.73, p < .001$. There were also significant interactions between duration range and stimulus duration, $F(6, 102) = 2.75, p < .02$, and between flicker, duration range, and stimulus duration, $F(6, 102) = 2.56, p < .02$.

In the 200/800-ms condition with the 8-year-olds, the effects of flicker, $F(1, 17) = 7.61$, $p < .02$, and stimulus duration, $F(6, 102) = 145.8, p < .001$, were significant, but the interaction between flicker and stimulus duration was not. In contrast, in the 400/1600-ms condition with this age group there was a significant Flicker × Stimulus Duration interaction, $F(6, 102) = 2.25, p < .05$, as well as significant effects of flicker, $F(1, 17) = 10.32, p < .01$, and stimulus duration, $F(6, 102) = 142.49, p < .001$, noted with this age group in the 200/800-ms condition.

Table 2 shows bisection points (stimulus durations that produced 50% "long" responses) for the different age groups, duration ranges values, and with and without preceding visual

TABLE 2
Bisection points derived by averaging the results of regression of individual subject data, regression of group data, or the mean of the two measures

	Bisection points[a]						
	3-year-olds		*5-year-olds*		*8-year-olds*		
	NF	*F*	*NF*	*F*	*NF*	*F*	*S/L*[a]
IREG	463	300	640	583	515	470	200/800
GREG	466	336	687	538	511	469	200/800
IREG	843	604	1092	911	915	781	400/1600
GREG	787	538	1077	938	883	816	400/1600
MEAN	464	318	663	560	513	470	200/800
MEAN	815	571	1084	924	899	798	400/1600

Note: Arithmetic means: 200/800-ms conditions, 500 ms; 400/1600-ms conditions, 1000 ms.
Geometric means: 200/800-ms conditions, 400 ms; 400/1600-ms conditions, 800 ms.
IREG = regression of individual subject data; GREG = regression of group data; MEAN = the mean of the two measures; NF = no flicker; F = flicker; S/L = values of short and long standards.
[a] In ms.

flicker. The bisection points were calculated in two different ways. Both followed Maricq et al.'s (1981) method; regression was performed on the steepest part of the psychophysical function, and the resulting slope and intercept values were used to calculate the bisection point. However, one of these (individual regression, IREG) used the psychophysical function from individual subjects to calculate the bisection point for each individual, and then averaged these points together. The other method, group regression (GREG), performed regression on psychophysical functions averaged over the group (i.e., on data in the form of the plot shown in Figure 1). The two methods did not always yield exactly the same values, mainly because of between-subject variability in the two younger subject groups but, as noted later, all the interesting trends in the bisection point data were present no matter how the bisection points were calculated. In addition, the bisection points derived from the two different methods were then averaged together (MEAN in Table 2).

Several points are obvious on inspection of the bisection points. First, whatever method was used to calculate them, and at both duration ranges and all ages, preceding the stimulus to be judged with visual flicker reduced the bisection point value. This change of bisection points could be tested statistically using the IREG values, and this showed that bisection points were significantly lower after visual flicker than without it. ANOVA found a significant effect of flicker, $F(1, 35) = 34.69, p < .0001$, as well as a significant effect of stimulus range, $F(1, 35) = 137.41, p < .001$, and a significant Flicker × Duration Range interaction, $F(1, 35) = 5.74, p < .02$. The effect of age was also significant, $F(2, 35) = 23.31, p < .001$, but the Age × Flicker, Age × Duration Range interactions were not significant. A between-age comparison using Mann–Whitney U-tests showed that the bisection point values in the 5-year-olds were in general higher than the bisection points in the 3- and the 8-year-olds (5-year-olds, 806 ms; 3-year-olds, 553 ms; 8-year-olds, 670 ms; U = 2 and 27, both $p < .001$).

Second, the degree of leftward shift of the bisection points (i.e., the difference between bisection point values in no-flicker and flicker conditions) was greater for the 400/1600-ms than for the 200/800-ms condition. For example, considering the MEAN values, the leftward shift was 146, 103, or 43 ms for the 3-, 5-, and 8-year-olds, respectively, in the 200/800-ms conditions but 244, 160, and 101 ms in the 400/1600-ms conditions. That is, the leftward shift of bisection points was around twice as great in the 400/1600-ms condition than in the 200/800-ms condition. Using the IREG bisection point values for statistical analysis, the difference between the bisection points with and without flicker in the 400/1600-ms and 200/800-ms conditions was found to be significant. When bisection points from the three age groups were combined into a single group, Wilcoxon tests showed that the bisection point was lower with flicker than without flicker for the 200/800-ms condition, $Z = 3.72$, $p < .001$, and for the 400/1600-ms condition, $Z = 3.98$, $p < .001$. The bisection point was reduced by a mean of 76.68 ms and 172.32 ms in the 200/800 and the 400/1600-ms conditions, respectively. The magnitude of the difference in the bisection points between the flicker and the no-flicker conditions was significantly greater in the 400/1600-ms condition than in the 200/800-ms condition (Wilcoxon test, $Z = 2.53$, $p < 0.01$). Expressed as a percentage of the no-flicker bisection point, this leftward shift in bisection point was roughly constant (i.e., 0.14 and 0.18 for the 200/800-ms and the 400/1600-ms conditions, respectively).

Comparing bisection points with the arithmetic and geometric means of S and L suggests that in no-flicker conditions the majority of the bisection points were closer to the arithmetic than to the geometric means. Of the 18 no-flicker bisection points (three age-groups, two duration ranges values, and three methods of calculation) 13 were closer to the arithmetic mean than to the geometric mean. When flicker was used, in contrast, 13/18 bisection points were closer to the geometric mean than to the arithmetic mean, consistent with the leftward shift in bisection points occasioned by flicker.

Psychophysical functions from bisection experiments can be analysed to yield two other performance measures in addition to the bisection point. These are the *difference limen* and the *Weber ratio*, and both reflect temporal sensitivity. The difference limen can be conceived of as the smallest duration difference that can be reliably discriminated amongst the durations in the set of stimuli used, a kind of "just noticeable difference". *Larger* values indicate *lower* temporal sensitivity. If timing is Weberian (i.e., conforms to scalar timing), then the difference limen should increase with increases in the duration range (i.e., limens should be larger in the 400/1600-ms conditions than in the 200/800-ms conditions). The difference limen is a measure of *absolute* temporal sensitivity, whereas the closely related Weber ratio is a measure of *relative* temporal sensitivity—that is, the just-noticeable difference expressed as some fraction of a measure of duration range, usually the bisection point. If Weberian timing holds, then the Weber ratio should remain constant as duration range changes.

The difference limen is calculated from the regression line used to derive the bisection point, and it is defined as half the difference between the duration that gives rise to 25% "long" responses and the duration that gives rise to 75% of such responses. The Weber ratio is derived from the difference limen divided by the stimulus duration giving rise to 50% "long" responses.

Calculation of the difference limen in our case is complicated by the fact that because some individual children, particularly some of the 3-year-olds, produced substantial proportions of "long" responses at the shorter stimulus durations, the duration value derived from the regression line that is calculated to give rise to 25% "long" responses was actually negative and therefore meaningless. To avoid this problem, and to calculate the difference limen and the

Weber ratio, we transformed the data from individual children as follows. One of the stimulus durations presented (often, but not necessarily, the shortest value used) gave rise to the lowest proportion of "long" responses, *x*% "long" (where *x* could, of course, be zero). We subtracted *x*% from the proportion of "long" responses from all the stimulus durations used for the condition analysed, to produce a transformed psychophysical function. For example, suppose that an individual child in the 200/800-ms condition produced 15% "long" at 200 ms (the smallest proportion of "long" responses), 25% at 300 ms, and so on, up to, say, 80% "long" at 800 ms. Given that 15% was the smallest proportion of "long" responses for this child, 15% would be subtracted from each proportion, making 0% at 200 ms, 10% at 300 ms, and so on, up to 65% at 800 ms. If the smallest proportion of "long" responses was zero, as it often was, particularly for the oldest children, then the psychophysical function was essentially untransformed.

This transformation method essentially shifted the psychophysical functions downwards, but kept their slope constant. The slope of the psychophysical function is, of course, a measure of temporal sensitivity, so the transformation method used enabled us to examine effects of age, duration range, and presence or absence of flicker on measures of temporal sensitivity while avoiding the negative stimulus duration values that could arise in analysis of untransformed data.

To produce the values used for group regression (GREG), the transformed psychophysical functions from each child were averaged together. For the IREG regression, the calculation was performed on data from individuals. The steepest part of the psychophysical function was used to derive the regression line, and parameters from the regression were used for subsequent calculation of the difference limen and Weber ratio. Resulting difference limens are shown in Table 3.

Inspection of the data in Table 3 suggests several conclusions. First, the GREG method always yielded higher difference limen values than did the IREG method, and although values from the two methods were often close, they were sometimes discrepant, particularly in data from the 3- and 5-year-olds. The higher values from GREG can be explained by the fact that the group psychophysical function, even after data transformation, was composed of

TABLE 3
Difference limens derived by averaging the results of regression of individual subject data or regression of group data

	Difference limens[a]						
	3-year-olds		*5-year-olds*		*8-year-olds*		
	NF	*F*	*NF*	*F*	*NF*	*F*	*S/L*[a]
IREG	210	290	174	178	124	110	200/800
GREG	219	297	234	233	137	146	200/800
IREG	168	377	288	285	224	227	400/1600
GREG	475	676	412	357	234	256	400/1600

Note: All calculations were carried out on transformed data, as described in the text. IREG = regression of individual subject data; GREG = regression of group data; NF = no flicker; F = flicker; S/L = values of short and long standards.

[a] In ms.

individual psychophysical functions, which were sometimes irregular, particularly in the younger children, whereas these irregularities tended not to occur on the steepest part of the individual psychophysical functions, so made less of a contribution to the IREG values. Second, for the 5- and 8-year-olds, the difference limens were clearly higher for the 400/1600-ms condition than for the 200/800-ms one, and this was also true for the 3-year-olds, with the exception of results from the no-flicker conditions calculated by the IREG method. Third, the oldest children tended to exhibit lower difference limens (i.e., higher temporal sensitivity) than the younger children. Fourth, the effect of flicker, on difference limen was not completely consistent and often very small.

Most of these suggestions were confirmed by statistical analysis of the difference limens obtained by the IREG method. We first conducted an overall ANOVA with duration range (200/800 ms or 400/1600 ms) and presence or absence of flicker as within-subject factors, and age as a between-subject factor. There were significant main effects of duration range, $F(1, 35) = 17.59$, $p < .001$, flicker, $F(1, 35) = 13.30$, $p < .001$, and age, $F(2, 35) = 11.38$, $p < .001$, and a significant interaction between flicker and age, $F(1, 35)$, $p < .001$, but the other interactions, (Duration Range × Age, Duration Range × Flicker, and Duration Range × Flicker × Age) were not significant.

Although the effect of duration range (difference limens tending to be larger at 400/1200 ms than at 200/800 ms) and age were obvious from inspection of Table 3, some of the other effects become clearer when simpler ANOVAs were performed. Consider data from the 3-year-olds. For these there was a significant effect of flicker, $F(1, 8) = 17.79$, $p < .01$, but no significant effect of duration range, nor a duration range by flicker interaction. For the 5-year-olds, in contrast, there was a significant effect of duration range, $F(1, 10) = 10.79$, $p < .01$, and this was the only significant effect. The same was true for the 8-year-olds, where the only significant effect was that of duration range, $F(1, 17) = 66.71$, $p < .001$. It seems, therefore, that the source of all the significant effects of flicker on difference limen came from the 3-year-olds.

We next compared the age groups two by two. In a comparison between the 3- and 8-year-olds, there were significant effects of age, $F(1, 25) = 20.59$, $p < .001$, duration range, $F(1, 25) = 7.93$, $p < .01$, and flicker, $F(1, 25) = 21.26$, $p < .001$, as well as significant interactions between flicker and age. These results show that the difference limens were lower in the 8-year-olds than in the 3-year-olds, and the other significant effects (duration range and flicker) were as expected from the presence of the 8-year-olds and 3-year-olds in the comparison. When 5- and 8-year-olds were compared, there were only significant effects of duration range, $F(1, 27) = 49.61$, $p < .001$, and age, $F(1, 27) = 13.81$, $p < .01$, indicating that the 8-year-olds had lower difference limens than the 5-year-olds. When the 3- and 5-year-olds were compared, there were no significant effects of age, the effect of duration range just failed to reach significance, $F(1, 18) = 3.98$, $p = .06$, and there were significant effects of flicker and flicker by age interaction, presumably resulting from the 3-year-olds.

Table 4 shows the Weber ratio (the difference limen divided by the bisection point), although in the present case we used the calculated stimulus duration that would have given rise to 50% “long” responses from the transformed data, not the bisection points shown in Table 2. The picture presented by the Weber ratios on inspection is reminiscent of that presented by the difference limens in some respects: There were some discrepancies between the values obtained from IREG and GREG calculations, although these were often similar; there

TABLE 4
Weber ratios derived by averaging the results of regression of individual subject data or regression of group data

	Weber ratios						
	3-year-olds		*5-year-olds*		*8-year-olds*		
	NF	*F*	*NF*	*F*	*NF*	*F*	*S/L*[a]
IREG	.35	.26	.26	.30	.24	.21	200/800
GREG	.37	.41	.31	.36	.26	.29	200/800
IREG	.25	.29	.25	.27	.23	.24	400/1600
GREG	.39	.38	.33	.33	.26	.28	400/1600

Note: All calculations were carried out on transformed data, as described in the text. IREG = regression of individual subject data; GREG = regression of group data; NF = no flicker; F = flicker; S/L = values of short and long standards.

[a] In ms.

was no obvious effect of flicker, and there was a suggestion of an age effect, in that the 8-year-olds seem to have lower Weber ratios than do the younger children. There was, however, little suggestion of a difference between the Weber ratios obtained at the different duration ranges.

Most of these suggestions were confirmed by statistical analysis. We first performed an overall ANOVA of the IREG-derived Weber ratios, with age as a between-group factor, and presence or absence of flicker and stimulus range as within-subject factors. There was a significant effect of age, $F(2, 35) = 10.06$, $p < .001$, and this was the only significant main effect: Neither flicker nor duration range produced significant results. Apart from the age effect, the only significant effect was a just-significant flicker by duration range interaction, $F(1, 35) = 4.25$, $p < .05$.

Considering the different age groups separately, the only significant effect obtained in any group was a just significant flicker by duration range interaction in the 3-year-olds, $F(1, 8) = 5.52$, $p < .04$. No other main effects or interactions were significant; that is, neither presence or absence of flicker nor duration range had any significant effect on Weber ratios.

We then performed two by two age group comparisons. Effects were similar to those found with the difference limen measures: There were significant age effects in comparisons between the 3- and 8-year-olds, $F(1, 25) = 29.92$, $p < .001$, and between the 5- and 8-year-olds, $F(1, 27) = 7.86$, $p < .01$, but no significant differences between the 3- and 5-year-olds, $F(1, 18) = 1.01$. There were also no other significant effects except a flicker by duration range interaction in the 3- and 8-year-olds comparison.

Overall, therefore, the difference limen and Weber ratio measures showed increasing temporal sensitivity between the ages of 5 and 8 years, and an effect of duration range on difference limen (the absolute sensitivity measure) but not the Weber ratio (the relative measure). Only the 3-year-olds showed any overall effect of flicker on difference limen, and this result produced some significant interactions between flicker and age when the 3-year-olds were involved in comparisons. The 3-year-olds also showed a significant flicker by duration range interaction (flicker decreased Weber ratios in the 200/800-ms condition but increased them slightly in the 400/1600-condition, see Table 4), and this effect also produced some age-related interactions when the 3-year-olds were included in comparisons. The older children showed no effect of flicker on either difference limen or Weber ratio. Why these effects should occur in 3-year-olds alone is unclear.

The effect of duration range on difference limen and lack of effect of duration range on Weber ratio are results that are both consistent with underlying constant sensitivity scalar timing of behaviour at all ages. The lack of change in Weber ratio with changes in stimulus range is one indication of underlying scalar timing, the other being superimposition, discussed as follows.

The bisection points in Table 2 can be used to provide a test of superimposition, which, according to Allan and Gibbon (1991), is the most appropriate method when bisection is used. This involves dividing each stimulus duration presented by the bisection point appropriate to the condition employed, then plotting the proportion of "long" responses against these transformed duration values. To do this, we used the MEAN bisection point value shown in Table 2. The resulting plots are shown in Figure 2.

The top, middle, and bottom panels of Figure 2 show data from the 3-, 5-, and 8-year-olds, respectively, and within each panel data from the four conditions used with each age group (200/800-ms and 400/1600-ms with and without flicker) are plotted together. Inspection of the resulting plots suggests that the data superimposed well. In the 8-year-olds, superimposition appeared close to perfect, and there was little deviation of any particular condition from the overall shape of the plot in either the 3- or the 5-year-olds. Although there were some outlying points in the 3-year-olds, from the flicker conditions (caused by the low bisection point values obtained), the points appeared to continue the general shape of the curve rather than deviating from it. This superimposition held over changes in the shape of the psychophysical functions in the different age groups (e.g., see Figure 1).

Discussion

The results support several conclusions. First, the bisection method with short-duration stimuli can produce orderly data from children as young as 3 years of age, providing that subjects who fail to show even rudimentary sensitivity to duration can be discarded. Second, a number of age effects could be noted, such as more rapid learning of the original *S*/*L* discrimination with increasing age (Table 1), psychophysical function slopes that increase with increasing age (Figure 1), and increases in temporal sensitivity (assessed by difference limens and the Weber ratios), at least between the ages of 5 and 8 years. Third, in spite of age-related differences in bisection performance, preceding stimuli to be judged by visual flicker generally increased the proportion of "long" responses, shifted psychophysical functions leftwards (Figure 1), and lowered bisection point values (Table 2). Fourth, the bisection point shift occasioned by flicker was greater with the 400/1600-ms *S*/*L* pair than with the 200/800-ms pair. Finally, data from the different conditions used within each age group superimposed well when MEAN bisection points were used to normalize stimulus durations (Figure 2).

Some of the effects noted here can be compared with those obtained in previous studies. McCormack et al. (1999) used children of 5, 8, and 10 years of age in a bisection procedure with *S*/*L* values of 200 and 800 ms. Like the present study, it was found that psychophysical functions tended to be flatter in the younger children, and bisection points were usually closer to the arithmetic than to the geometric means of *S* and *L*. Droit-Volet and Wearden (2001) studied 3-, 5-, and 8-year-olds on bisection with *S* and *L* values of 1 and 4 s, or 2 and 8 s. The results

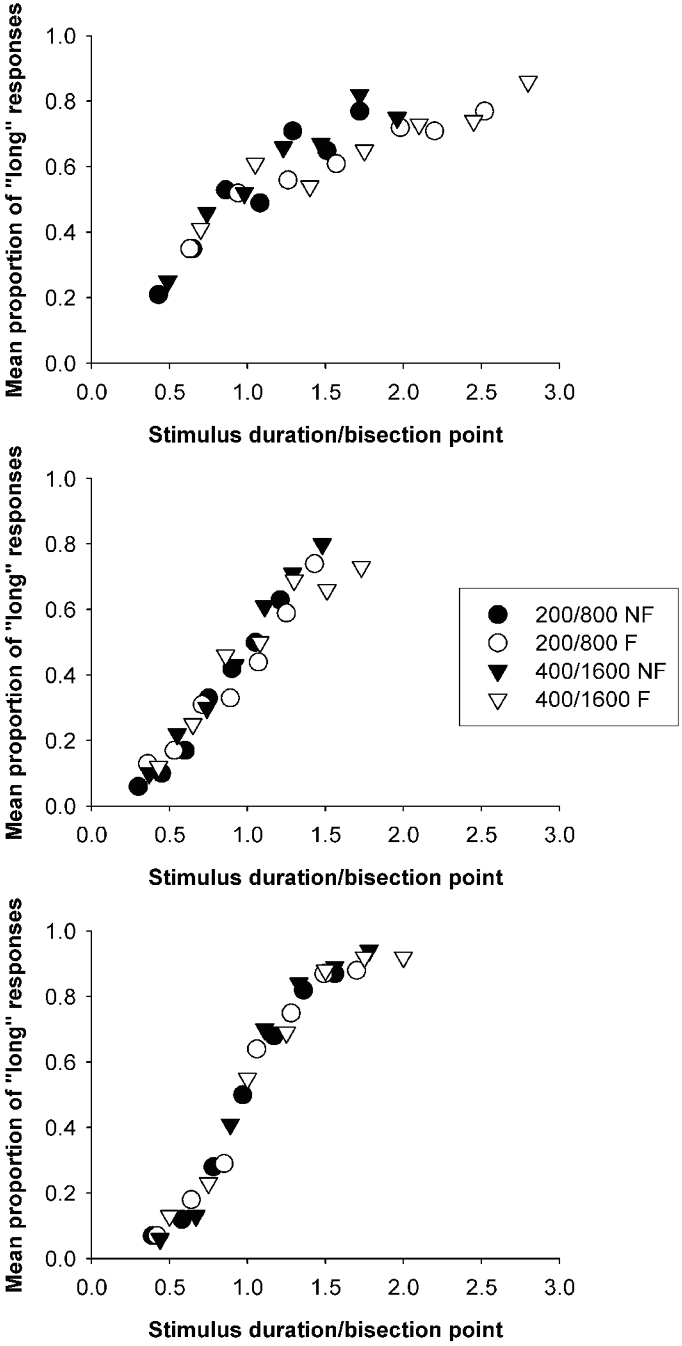

Figure 2. Proportion of "long" responses plotted against stimulus duration divided by the bisection point appropriate for the condition plotted (MEAN in Table 2 was used). Top panel: data from 3-year-olds; centre panel: data from 5-year-olds; lowest panel: data from 8-year-olds.

resembled those shown in Figure 1: The younger children had flatter and more irregular psychophysical functions. Furthermore, Weber ratios were higher in the 3- and 5-year-olds than in the 8-year-old children (cf., the present Table 3 with Table 2 from Droit-Volet & Wearden, 2001). Other similarities were that the younger children also learned the original *S*/*L* discrimination more slowly than did the older children, and bisection points were closer to the arithmetic than to the geometric means, in most cases, as in the present work. In spite of the use of two different *S*/*L* pairs, which allowed superimposition to be tested, the data obtained from the two younger groups by Droit-Volet and Wearden were ambiguous with respect to the question of superimposition. It seems therefore that the use of shorter durations in bisection makes manifestation of superimposition clearer than when longer durations are employed (e.g., the present Figure 2). However, in other studies using a temporal generalization method, Droit-Volet (in press), and Droit-Volet et al. (2001), found clear superimposition even in 3-year-olds. The data shown in the present Figure 2 are the first to demonstrate good superimposition in young children and hence conformity to scalar timing with a bisection method.

Our data show that preceding a stimulus to be judged with visual flicker appears to increase its subjective duration. This demonstration, the first of its type in children, joins a number of other studies that have shown that preceding or accompanying stimuli to be timed, or timed responses, by repetitive stimulation (usually in the form of periodic clicks) makes subjective duration longer (e.g., Burle & Bonnet, 1997, 1999; Penton-Voak et al., 1996; Treisman et al., 1990, 1992, 1994; Wearden et al., 1998, 1999). The effect of periodic repetitive stimulation is very general, having similar effects on the timing of auditory and visual stimuli (Penton-Voak et al., 1996; Wearden et al., 1998), affecting response as well as stimulus timing (e.g., Burle & Bonnet, 1997, 1999; Penton-Voak et al., 1996; Treisman et al., 1992), and producing the same sort of changes across a range of different procedures for assessing timed behaviour (e.g., Penton-Voak et al., 1996; Wearden et al., 1999). According to the results presented earlier, this generality can now, apparently, be extended to children as young as 3 years. As it seems highly unlikely that our 3- and 5-year-olds have any complex response strategies that might be affected by the flicker (Droit, 1994; Droit-Volet, 1998, 2000), our results suggest that the repetitive stimulation operates at a fundamental perceptual level, changing the subjective duration of events in a very direct way.

If some manipulation affects subjective time by making stimuli seem to last longer than they would otherwise, pacemaker–accumulator internal clock theory suggests two ways in which the clock might be affected (as discussed in more detail elsewhere, see Wearden et al., 1998, pp. 103–104). One of these is an increase in pacemaker speed; that is, the pacemaker produces more "pulses" per unit time with the manipulation than without. Alternatively, the manipulation may affect the switch of the internal clock, which connects the pacemaker and accumulator. For example, the manipulation may make the switch close earlier than normal, or open later. Both effects would increase the number of pulses accumulated during the event to be judged compared with a control condition. However, the mathematics of internal clock models suggests that a distinction can be made between the two effects. Pacemaker speed effects are multiplicative with real time, so if the pacemaker is "speeded up" by some manipulation, the effect should be absolutely greater at longer times than at shorter times. Switch effects, on the other hand, are independent of the durations judged and are additive, and thus they are constant whatever duration values are employed.

To distinguish the two possibilities, behaviour at more than one duration value, or range of values, must be observed. The clearest demonstrations that some manipulations can affect pacemaker speed probably come from (1) drug studies with animals and (2) studies using verbal estimation methods with humans. For example, Maricq et al. (1981) used amphetamine to apparently increase pacemaker speed in rats. They employed a bisection method with *S*/*L* pairs of 1 and 4 s, 2 and 8 s, and 4 and 16 s. In all cases, administration of amphetamine shifted psychophysical functions to the left, with the shift being greater with the longer *S*/*L* values (see Maricq et al., Figure 7, p. 26). Maricq et al. (p. 26) also discussed bisection point shifts occasioned by amphetamine and noted that these were greater with longer *S*/*L* values. This effect is exactly that required by changes in pacemaker speed and, of course, the effect obtained in our own study. The obvious implication is that the flicker increased pacemaker speed in children, just as amphetamine did when administered to rats.

Clear demonstrations of pacemaker speed effects, of which the present experiment seems to be one, are actually rather rare in studies both with repetitive stimulation and with drugs. Penton-Voak et al. (1996) used clicks to influence subjective time, and assessed behaviour using a variety of methods. Only one of these, verbal estimation, produced conclusive evidence of pacemaker speed changes (although the other methods all showed that stimuli were judged as longer afterclicks) probably because it was the only one to use a large enough stimulus range (more than 15-fold) to observe the multiplicative effect clearly and test it statistically (e.g., see Penton-Voak et al., Figure 4, p. 315; for a replication, see Wearden et al., 1998). Other studies, including experiments in the study of Penton-Voak et al. (1996) have been generally focused on other issues (e.g., interference effects of specific stimulation frequencies, Burle & Bonnet, 1997, 1999; Treisman et al., 1990, 1992, 1994; whether the rate of subjective time could be decreased as well as increased, Meck, 1983; Wearden et al., 1999). It seems reasonable on the basis of existing data that both amphetamine in animals (Maricq et al., 1981) and repetitive stimulation in humans (Penton-Voak et al., 1996) do change pacemaker speed, but the possibility exists that both drugs and repetitive stimulation have effects in addition to pacemaker speed changes.

The bisection study of Maricq et al. (1981), using rats as subjects and amphetamine to change pacemaker speed, also produced difference limen and Weber ratio data which resembled those obtained in the present study. As mentioned earlier, the difference limen is a measure of temporal sensitivity reflecting the smallest change that can be discriminated among the range of stimuli used. If Weber's Law holds, then the difference limen would be expected to be sensitive to stimulus range, and this was exactly what Maricq et al. (1981, p. 25) reported; the difference limen values increased with increases in the stimulus durations employed. Weber ratios, on the other hand, remained constant, again a result consistent with Weber's Law. An additional finding of Maricq et al. (1981, see also Meck, 1983, p. 178) was that the amphetamine manipulation, which shifted bisection points, presumably by increasing pacemaker speed, left Weber ratios and difference limens largely unaffected. Our data were very similar in almost all these respects. Difference limen increased with increasing stimulus duration values (Table 3), except when results from the 3-year-olds were derived from the IREG method, but Weber ratios (Table 4) were not affected. Furthermore, presence or absence of flicker never had any significant effect on either difference limen or Weber ratio in the 5- and 8-year-olds in our study (Tables 3 and 4).

Overall, therefore, the results of the present study illustrate the usefulness of internal clock approaches as explanations of at least some aspects of human timing behaviour. The behaviour of children as young as 3 years appears to conform reasonably well to the principles of scalar timing (see also Droit-Volet, in press, and Droit-Volet et al., 2001) and, furthermore, even the youngest children that we have studied appear to have a functioning internal clock, which can "speeded up" in the same way as has been demonstrated in previous studies with both humans and animals. The fact that the flicker manipulation changed subjective time in a similar way in all the age groups studied here suggests that the operation of the putative internal clock is independent of age, at least within the age range that we have studied. This constancy of clock processes across the age range implies that developmental changes in timed behaviour are caused by changes elsewhere than in the internal clock, for example, at the level of processing of the temporal information, such as attention to time, or memory for temporal information—processes that have previously been shown to exhibit developmental changes (Droit-Volet & Rattat, 1999; Gautier & Droit-Volet, 2002; Rattat & Droit-Volet, 2001).

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