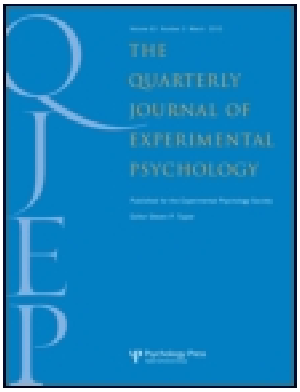

The Quarterly Journal of Experimental Psychology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/pqje20

Time, number and length: Similarities and differences in discrimination in adults and children

Sylvie Droit-Volet [a] , Angélique Clément [a] & Michel Fayol [a]

[a] Blaise Pascal University, Clermont-Ferrand, France

Version of record first published: 19 Nov 2008.

To cite this article: Sylvie Droit-Volet, Angélique Clément & Michel Fayol (2008): Time, number and length: Similarities and differences in discrimination in adults and children, The Quarterly Journal of Experimental Psychology, 61:12, 1827-1846

To link to this article: http://dx.doi.org/10.1080/17470210701743643

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
2008, 61 (12), 1827–1846

Psychology Press
Taylor & Francis Group

Time, number and length: Similarities and differences in discrimination in adults and children

Sylvie Droit-Volet, Angélique Clément, and Michel Fayol
Blaise Pascal University, Clermont-Ferrand, France

The aim of this study was to focus on similarities in the discrimination of three different quantities—time, number, and line length—using a bisection task involving children aged 5 and 8 years and adults, when number and length were presented nonsequentially (Experiment 1) and sequentially (Experiment 2). In the nonsequential condition, for all age groups, although to a greater extent in the younger children, the psychophysical functions were flatter, and the Weber ratio higher for time than for number and length. Number and length yielded similar psychophysical functions. Thus, sensitivity to time was lower than that to the other quantities, whether continuous or not. However, when number and length were presented sequentially (Experiment 2), the differences in discrimination performance between time, number, and length disappeared. Furthermore, the Weber ratio values as well as the bisection points for all quantities presented sequentially appeared to be close to that found for duration in the nonsequential condition. The results are discussed within the framework of recent theories suggesting a common mechanism for all analogical quantities.

Keywords: Time; Number; Length; Quantity; Perception.

There is now ample evidence that young children have a lower sensitivity to time than adults in temporal discrimination tasks (e.g., Droit-Volet, Clément, & Wearden, 2001; Droit-Volet, Meck, & Penney, 2007a; Droit-Volet & Wearden, 2001; McCormack, Brown, Maylor, Darby, & Green, 1999; McCormack, Brown, Smith, & Brock, 2004; Rattat & Droit-Volet, 2005). However, until now, no researcher has been able to offer a clear explanation of why young children have lower sensitivity to time (for a recent review, see Droit-Volet, Delgado, & Rattat, 2006). This failure results to a large extent from our difficulty in understanding what time is. At the beginning of the last century, psychologists believed that duration is not a primitive cue but is derived from other dimensions, such as the number of perceived changes or movements in space associated with speed (e.g., Fraisse, 1967; Ornstein, 1969; Piaget, 1946). The development of the ability to process time accurately has thus been attributed to the development of logical reasoning, which allows children to correctly induce duration from other dimensions.

Correspondence should be addressed to Sylvie Droit-Volet, Laboratoire de Psychologie Sociale et Cognitive, CNRS (UMR 6024), Université Blaise Pascal, 34 avenue Carnot, 63037 Clermont-Ferrand Cedex, France.
E-mail: droit-volet@ univ-bpclermont.fr

The authors extend their gratitude to the inspector of the state education system, as well as to the staff of a number of schools: the Mirefleurs, Beauséjour, Paul Bert Schools in Vichy, and the Victor Hugo, Jules Ferry, and Jacques Prévert schools in Clermont-Ferrand.

http://www.psypress.com/qjep
DOI:10.1080/17470210701743643

Since then, studies have provided strong evidence that young children, just like animals and human adults, are able to process the duration of an event as an item of information per se, when the other dimensions are controlled (Brannon, Roussel, & Meck, 2004; Colombo & Richman, 2002). Furthermore, despite their lower sensitivity to time, children's temporal behaviour exhibits the same fundamental properties as those observed in both animals and human adults—that is, (a) mean accuracy and (b) temporal scalar variance (e.g., Clément & Droit-Volet, 2006; Droit-Volet, 2002; Droit-Volet & Wearden, 2001). The scalar variance is the requirement that the variability of discriminative judgement is proportional to stimulus magnitude, such that the coefficient of variation of time estimates (Weber ratio) remains constant as the range of to be-judged durations varies (Gibbon, 1977; Gibbon, Church, & Meck, 1984; for a recent review, see Lejeune & Wearden, 2006). On the basis of these results, a clear consensus has emerged according to which the representation of time involves a specialized internal clock mechanism that is functional at an early age.

Since then, research into time has been independent of research into the other dimensions. However, we are currently witnessing a revival of interest in the study of the relationships between different types of dimensions. This renewed interest is mainly due to new results showing similarities in the comparison judgements of different type of quantities, both discontinuous and continuous, such as number or size. Indeed, a number of behavioural studies have revealed strong similarities in the characteristics of comparison judgements between number (a set of elements) and size (set size, line length). Furthermore, recent functional magnetic resonance imaging (fMRI) studies have identified a considerable overlap in the neural substrates, housed in the parietal cortex, involved in the representation of different quantities—namely, number (numerical value) and size (size of digits; Dehaene, Piazza, Pinel, & Cohen, 2003; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Kadosh et al., 2005; Pinel, Piazza, Le Bihan, & Dehaene, 2004). This has led several researchers to suppose the existence of "a common mechanism for all the quantities" (Gallistel & Gelman, 2000; Hubbard, Piazza, Pinel, & Dehaene, 2005; Walsh, 2003a, 2003b).

Although time is also a quantity represented through a mental magnitude with scalar variability, in the same way as number and size, very few studies have examined similarities between discrimination judgements for duration and the other quantities in humans. A few studies have nevertheless tried to compare time and number in a bisection task initially in animals (Breukelaar & Dalrymple-Alford, 1998; Fetterman & Killeen, 1992; Meck & Church, 1983; Meck, Church, & Gibbon, 1985; Roberts & Boisvert, 1998; Roberts & Mitchell, 1994; for a recent review, see Fetterman, 2006) and, more recently, in human adults (Balci & Gallistel, 2006; Brown, McCormack, Smith, & Stewart, 2005; Roitman, Brannon, Andrews, & Platt, 2007) and in children (Droit-Volet, Clément, & Fayol, 2003). In this bisection task, the subjects were trained to discriminate a few/short standard (e.g., a sequence of two signals of 2-s duration) from a many/long standard (a sequence of eight signals of 8-s duration). They were then presented with comparison stimuli (intermediate values or values equal to the standard), with either the number or the time varying while the other dimension was held constant. This bisection task revealed that the subjects were able to simultaneously process time and number in a sequence of stimuli, and this as young as 5 years of age. Furthermore, and more interestingly for our purposes, in animals and young children, the bisection yielded psychophysical functions for time and number that superimposed well, thus indicating equivalent levels of discrimination for time and number—that is, with the same index of sensitivity (Weber ratio). In human adults, sensitivity to time nevertheless seems to lag behind sensitivity to number, thus suggesting that number tends to become a more salient cue than time (Droit-Volet et al., 2003; Roitman et al., 2007).

The similarity between the discrimination of number and time in bisection led Meck and Church (1983) to propose a new model (mode-control model) to account for both time and number processing, based on the internal-clock model derived from the scalar timing theory (Gibbon, 1977; Gibbon et al., 1984). According to this model, the raw material for time and number is a quantity of pulses emitted by a pacemaker and accumulated in a counter. The differentiation between these two dimensions would originate in the mode of operation of the switch controlling the flow of pulses into the accumulator. For time, the switch closes at the onset of the stimulus and remains closed until its offset (run mode), thus resulting in an accumulator value representing overall elapsed time. For number, it closes briefly at the onset of each event (event mode), with the accumulator value representing the cumulative number of stimuli.

However, the problem affecting these bisection studies, which have identified similar psychophysical functions for number and duration, is that they used a sequence of events in which time was totally confounded with number (Breukelaar & Dalyrmple-Alford, 1998; Roberts, 1995, 1997). Indeed, they used a fixed number of events that occurred periodically (one signal cycle/s)—that is, at a certain frequency. Furthermore, the numerosity was not presented, as in the classical task on numerosity comparison judgements, in the form of a set of discrete objects presented simultaneously (static presentation), but in the form of a continuous flow of events that have to be added (i.e., sequential stimuli). We can therefore suppose that the processing of numerosity presented sequentially differed from a nonsequential presentation because it required a supplementary dynamic cognitive control in order to keep track of the stimulus flow. Because of its purely continuous nature, the processing of time thus differs from that of the other quantities (number and size). As revealed by a number of studies, the processing of time is particularly demanding in terms of attention because it requires a sustained attentional effort—that is, subjects must maintain the focus of attention across the continuous passage of time (e.g., Coull, 2004; Coull, Vidal, Nazarian, & Macar, 2004; Fortin, Bédard, & Champage, 2005). Furthermore, recent studies have suggested that young children's lower sensitivity to time is mainly due to noise in the encoding of time as a result of their limited attention or working-memory capacities (Delgado & Droit-Volet, 2007; Droit-Volet, 2003; Droit-Volet, Wearden, & Delgado-Yonger, 2007b; McCormack, Wearden, Smith, & Brown, 2005).

The purpose of this article was thus to compare, in children aged 5 and 8 years as well as in adults, the discrimination of duration with that of other quantities, both discontinuous, such as numerosity, and continuous, such as line-length, when these quantities are presented nonsequentially (a simultaneous presentation mode; Experiment 1) or sequentially (Experiment 2), so that the total number or length required accumulation across stimuli. We expected sensitivity to time to be lower than sensitivity to either number or line length when these latter quantities are presented in a nonsequential manner, especially in the younger children. Number and length should produce quite similar psychophysical functions as each other. For the sequential presentation, when numerosity and line length share the sequential characteristic of time, the differences in the slopes of the psychophysical functions between time, number, and line length should be decreased, and this in all the age groups, with the age-related effect being the same in the bisection of all the sequentially presented quantities.

EXPERIMENT 1

Method

Participants

The sample consisted of 220 participants: 68 five-year-olds (38 boys and 30 girls; mean age = 5.11, *SD* = 0.28); 74 eight-year-olds (36 boys and 38 girls; mean age = 7.97, *SD* = 0.39); and 78 adults (11 men and 67 women; mean age = 19.67, *SD* = 2.36). The children came from nursery and primary schools, and the adults were first-year psychology students from Blaise Pascal University, all in Clermont-Ferrand, France.

Materials

The participants sat in a quiet room in front of a computer, which controlled the stimulus presentation and recorded the data via PsyScope for Macintosh. The participants gave their responses to the stimuli by pressing two keys ("k" and "d") on the computer keyboard. For the "time" modality, the stimulus was a blue circle (2.5 cm in diameter) presented for a given duration (s). For the "number" modality, the stimulus was a pattern of a given number (n) of blue circles (each 1.0 cm in diameter), the spatial disposition of which was randomly determined for the test trials. For the "length" modality, the stimulus took the form of a blue line (0.5 cm in width) of a given length (cm). All the stimuli were presented in the centre of the computer screen. The "number" and the "length" stimuli were presented for a randomly chosen duration of 1, 2, or 3 s. For the training phase of the experiment, feedback was given in the form of a clown's face, which was either smiling (correct responses) or frowning (incorrect responses) and was displayed for 2 s in the centre of the computer screen.

Procedure

In each age group, the participants were randomly assigned to the time, number, or length bisection condition. The procedure was similar in all the bisection conditions, except for the stimulus that the participants had to judge: duration, number, or length stimulus. For each bisection modality, two subgroups of participants were formed and were assigned to a different range of stimulus values: 4/10 or 8/20. For the 4/10 range, the short/few standard was 4 (4 s, 4 n, 4 cm) and the long/many standard 10 (10 s, 10 n, 10 cm). The probe stimuli were 4, 5, 6, 7, 8, 9, and 10. For the 8/20 range, the standards were 8 and 20, and the probe stimuli 8, 10, 12, 14, 16, 18, and 20.

Before the testing phase, the participants were presented with the two standards, identified as the short/few and the long/many standard four times and were trained to discriminate between them. Each participant saw successive training blocks of eight trials (i.e., four for each standard), with a randomized order of presentation. A correct response resulted in the smiling-clown feedback and an incorrect one in the frowning-clown feedback, followed by the repetition of the trial event. A successful block of trials (i.e. one without any error) terminated training and was immediately followed by the bisection test.

For each modality condition, the bisection test consisted of 56 trials without feedback (i.e., eight blocks of 7 trials), with 1 trial for each probe stimulus. The probe stimuli were presented in a random order within each trial block. The intertrial interval was also randomly chosen between 1 and 3 s. As in the training phase, the participant pressed one key after the probe stimulus judged "short/few", and another key after the probe stimulus judged "long/many", the button-press order being counterbalanced. In addition, in both the training and testing phases, all the participants were told not to count. Furthermore, in order to suppress vocal and subvocal counting, they were told to produce repetitive speech aloud and as fast as possible. The experimenter controlled the continuity of their verbal activity (see Gallistel & Gelman, 2000).

Results and discussion

Table 1 shows the number of training blocks (8 trials per block) required to discriminate the short/few from the long/many standard for time, number, and length bisection in the two ranges of stimulus values. As in the other studies in humans using the temporal bisection task (e.g., Wearden & Bray, 2001), the number of trials required to discriminate the two standard durations was small: 1 block for the adults and between 1 and 3 blocks for the children. Furthermore, there was no effect of stimulus range (Mann–Whitney U, $U = 5{,}930.5$, $p > .05$), and this was verified in each age group for the different bisection modalities. The two standards were thus as easy to differentiate in the 4/10 as in the 8/20 stimulus range. Interestingly, the Kruskal–Wallis test revealed a significant effect of age, $\chi^2(2) = 16.91$, $p < .0001$. The 5-year-olds required more training blocks than the 8-year-olds, $U = 2{,}211$, $p < .02$, and the adults, $U = 2{,}262$, $p < .0001$, whereas the two older age groups required a similar number of training blocks, $U = 2{,}808$, $p > .05$. When each age group was taken separately, the Mann–Whitney test revealed that the

Table 1. *Number of training blocks required by each age group to meet the learning criterion in the training phase for the two stimulus ranges in each modality bisection*

		Age group								
		5 years			*8 years*			*Adults*		
Modality	*Stimulus range*	*M*	*Min*	*Max*	*M*	*Min*	*Max*	*M*	*Min*	*Max*
Time	4–10 s	1.71	1	3	1.00	1	1	1.00	1	1
	8–20 s	1.45	1	3	1.00	1	1	1.00	1	1
Number	4–10	1.00	1	1	1.08	1	2	1.00	1	1
	8–20	1.15	1	2	1.00	1	1	1.00	1	1
Length	4–10 cm	1.08	1	2	1.10	1	2	1.00	1	1
	8–20 cm	1.00	1	1	1.00	1	1	1.00	1	1

Note: M = mean. Min = minimum, Max = maximum number of training blocks. Learning criterion = 8 consecutive correct responses.

5-year-olds required more training blocks for time (1.58) than for either number (1.08), $U = 158$, $p < .02$, or length (1.04), $U = 139.5$, $p < .005$, the same number of training blocks being required for these last two modalities, $U = 301$, $p > .05$. Unlike in the 5-year-olds, the number of training blocks required was similar in the three modalities for the 8-year-olds and the adults (all $p > .05$). Therefore, the youngest children required more trials to discriminate between the two standards for time than for number or length.

Figure 1 shows the mean proportion of "long/many" responses plotted against the probe stimuli for the time, number, and length bisection conditions, for both the 4/10 and the 8/20 stimulus ranges, in the 5-year-olds (upper panel), the 8-year-olds (middle panel), and the adults (lower panel). An examination of Figure 1 suggests that the slope of the psychometric function was flatter in the 5-year-olds than in the 8-year-olds or the adults. However, irrespective of the age group and whatever the stimulus range tested, the psychophysical functions were flatter for time than for either number or length. We present here the analyses of Weber ratios and bisection points. Proportion of long responses was also analysed. However, because this measure produced very similar results to the Weber ratio and the bisection point, it is not presented here.

The bisection point, also called the point of subjective equality, is the stimulus value giving rise to a probability of long/many responses of .50. The Weber ratio is the ratio of the difference limen (half the distance between the stimuli that result in .25 and in .75 long/many choices) to the bisection point (stimulus with .50 long/many choices). The higher the Weber ratio is, the flatter the psychometric function, and the lower the sensitivity is. There are various ways of calculating the Weber ratio, but they lead to very similar results as demonstrated by Wearden and Ferrara (1995, 1996). In our experiment, we used the method introduced by Church and Deluty (1977) and employed by several authors since. The Weber ratio and the bisection point were calculated for each participant from the slope and intercept parameters obtained from a linear regression on the steepest section of the individual bisection function. Table 2 presents the obtained Weber ratios and bisection points.

Weber ratio

An overall analysis of variance (ANOVA)[1] was run on the Weber ratio with age, bisection

---

[1] Initial ANOVAs for the two groups of children revealed no main effect of sex or button-press, nor any interactions involving these two factors. Thus these factors were not included in the statistical analyses.

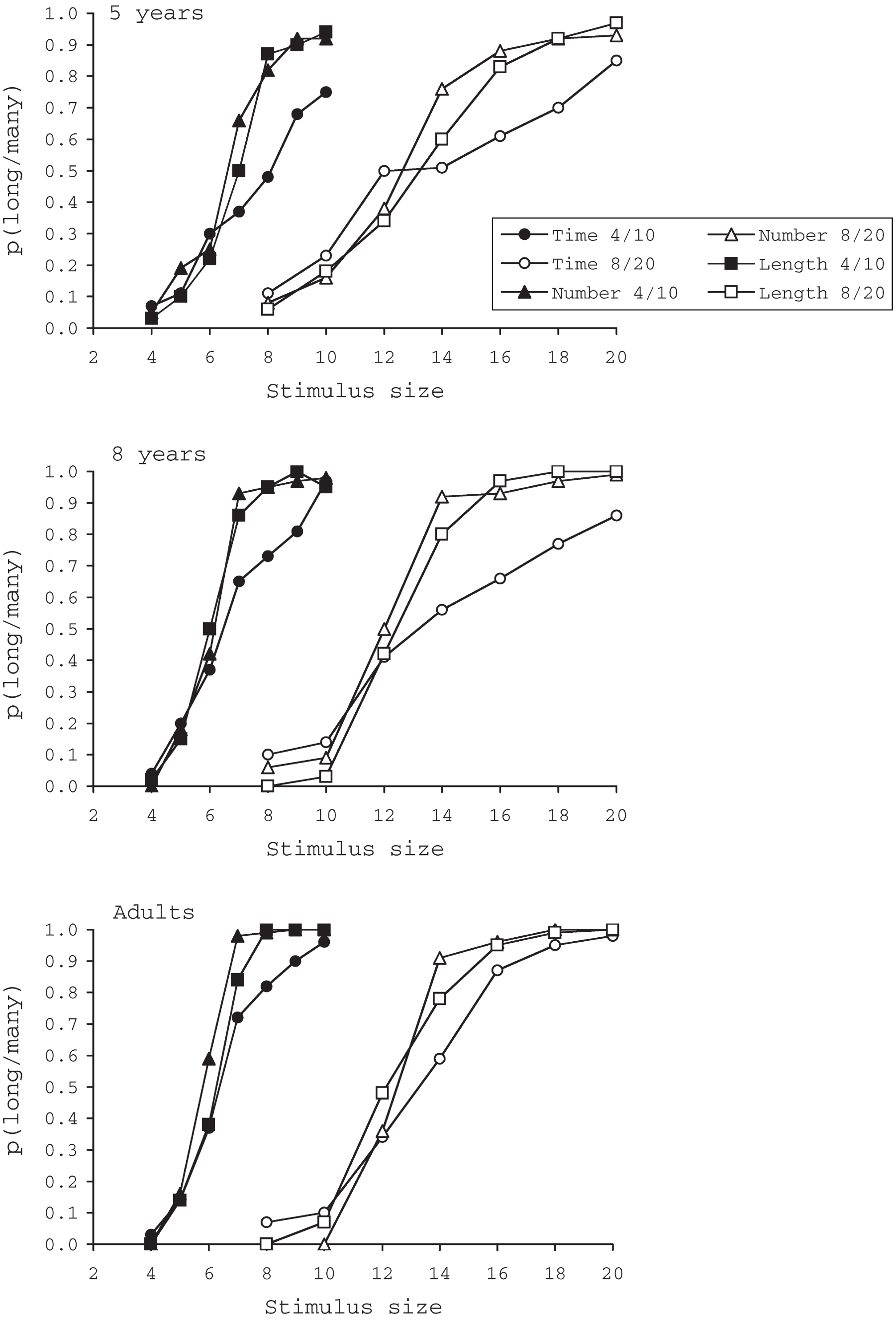

Figure 1. *Mean proportion of "long/many" responses plotted against probe stimulus when the stimuli were presented nonsequentially in each modality, for the 4/10 and the 8/20 ranges in the 5-year-olds, the 8-year-olds, and the adults.*

Table 2. *Means of Weber ratios and bisection points obtained by each age group in the different bisection conditions*

		Age group					
		5 years		*8 years*		*Adults*	
Modality	*Stimulus range*	*WR*	*BP*	*WR*	*BP*	*WR*	*BP*
Time	4–10 s	.28 (.08)	8.01 (1.01)	.25 (.07)	6.87 (1.05)	.17 (.05)	6.48 (0.90)
	8–20 s	.32 (.08)	14.31 (2.86)	.25 (.05)	14.40 (3.02)	.17 (.08)	13.20 (1.05)
Number	4–10	.17 (.05)	6.73 (0.80)	.12 (.07)	6.03 (0.57)	.09 (.04)	5.79 (0.50)
	8–20	.20 (.06)	12.78 (1.19)	.13 (.06)	12.05 (1.11)	.08 (.02)	12.52 (0.86)
Length	4–10 cm	.15 (.08)	6.98 (0.68)	.08 (.04)	6.01 (0.85)	.08 (.04)	6.13 (0.71)
	8–20 cm	.14 (.09)	13.29 (2.07)	.07 (.01)	12.49 (1.49)	.06 (.03)	12.48 (1.71)

Note: WR = Weber ratios; BP = bisection points. The arithmetic mean and the geometric mean for the 4–10 pair were 7 and 6.32, respectively, and for the 8–20 pair, 14 and 12.65. Standard deviations are in parentheses.

modality, and stimulus range as between-subjects factors. There was a significant main effect of age, $F(2,\ 201) = 52.88$, $p < .0001$, and of modality, $F(2,\ 201) = 111.925$, $p < .0001$, as well as a significant interaction between age and modality, $F(4,\ 201) = 2.73$, $p < .03$. The two-by-two age comparisons using the Scheffé post hoc tests revealed that, for each modality (time, number, and length), the Weber ratio values were significantly higher in the 5-year-olds (.30, .19, .14, respectively) than in the 8-year-olds (.25, .13., .07) or the adults (.17, .09, .07; all $p < .04$). The Weber ratios were also greater in the 8-year-olds than in the adults for time and number (both $p < .05$), but not in the length condition in which the Weber ratios appeared to be similar in these two age groups ($p > .05$). Thus, discrimination sensitivity improved with age in a bisection task, whatever the modality tested.

In addition, the post hoc Scheffé tests revealed that the Weber ratio was greater for time than for either number or length in all age groups: in the 5-year-olds (.30 vs. .19 vs. .14, respectively, all $p < .0001$), the 8-year-olds (.25 vs. .13 vs. .07, all $p < .001$), and the adults (.17 vs. .09 vs. .07, all $p < .001$). Whatever the age group tested, sensitivity in the bisection task was thus lower for time than for the other dimensions. Although the number was a discontinuous magnitude and the length a continuous one, the Weber ratio values for these two magnitudes were similar, with the difference not being significant in the 5-year-olds or adults (both $p > .05$). However, the 8-year-olds did exhibit a significantly lower Weber ratio for number than length (.07 vs. 13, $p < .01$).

The overall ANOVA showed neither a main effect of range, $F(1, 201) = 0.21$, $p > .05$, nor any interaction involving this factor—that is, Range × Age, Range × Modality, And Range × Age × Modality, highest $F = 1.02$, $p > .05$. Thus, the Weber ratio remained constant as the absolute stimulus value increased, and this for all the modalities and age groups tested. These findings are exactly those required by the scalar property of variance (i.e., a form of Weber's law). Another test allowing us to examine the scalar property is the superposition test—that is, the test of whether data from judgements of different absolute values superimpose well when plotted on the same relative scale. This is performed by dividing the stimulus value by the shortest probe stimulus (Church & Deluty, 1997). Figure 2 presents the data for the three age groups and for each dimension resulting from this test. An examination of Figure 2 suggests that the bisection functions for the different absolute values superimposed well across all conditions, with the possible exception of the 5-year-olds in the case of time. The variability of the temporal discriminations in the 5-year-olds appeared to be greater for the 8/20 than for the 4/10 duration range. However, the difference in the Weber ratio between these two duration ranges did not reach

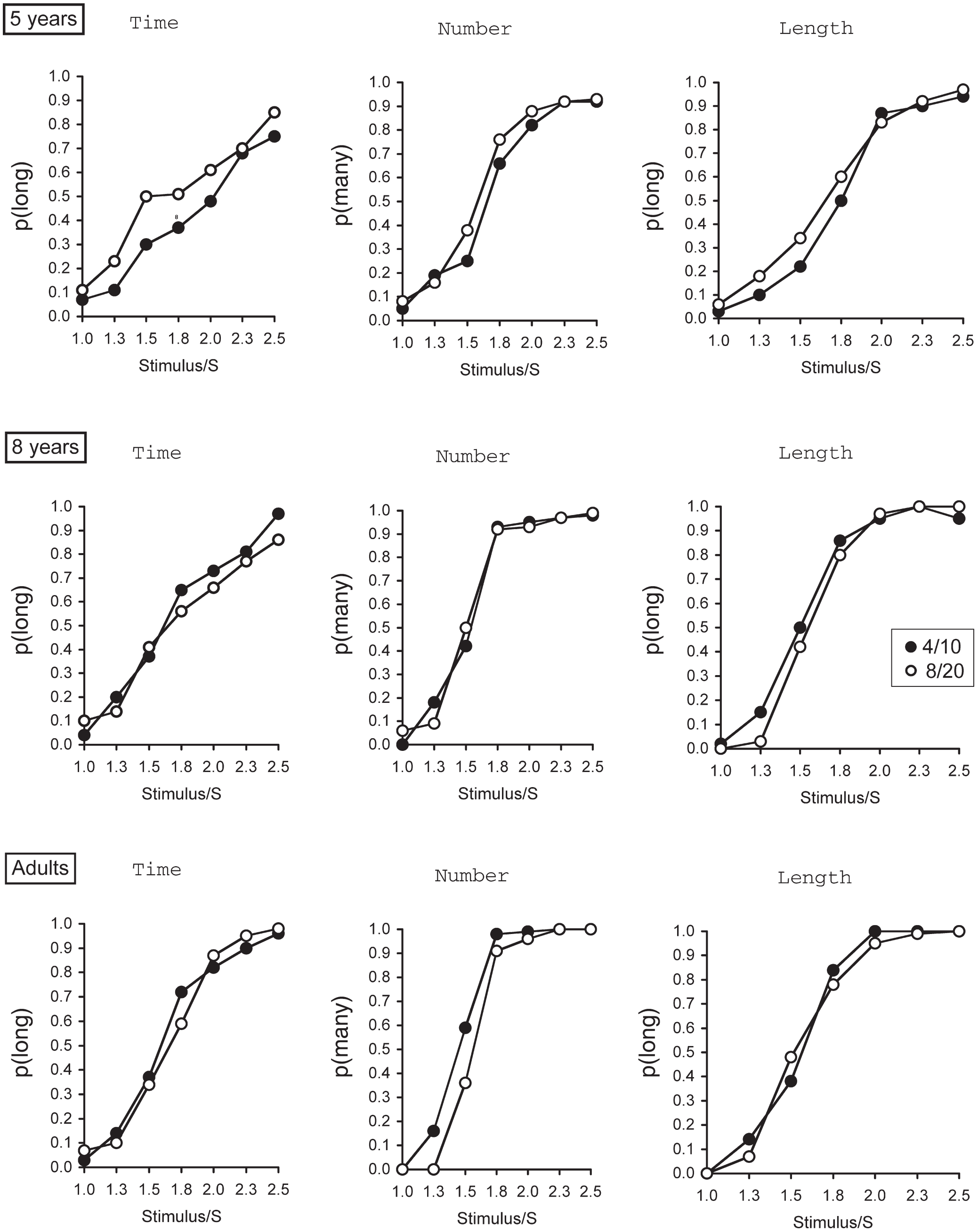

Figure 2. *Psychophysical functions obtained for the three age groups plotted against probe stimulus divided by the shortest stimulus value when the stimuli were presented nonsequentially for the 4/10 and the 8/20 ranges for time (left panel), number (middle panel), and length (right panel).*

significance, $t(16) = 0.93$, $p > .05$. Thus, whatever the magnitude considered, the bisection performance exhibited the scalar property of variance and this as early as 5 years of age.

Bisection point

The overall three-way ANOVA on the bisection point showed a significant main effect of age, $F(2, 202) = 7.87$, $p < .0001$, and of modality, $F(2, 202) = 14.92$, $p < .0001$. No two- or three-way interactions were significant. Thus the bisection point value was shifted toward the right and was close to the arithmetic mean (10.5) in the 5-year-olds, compared to the 8-year-olds (10.35 vs. 9.64, collapsed across modality stimuli) and the adults (10.35 vs. 9.43; both $p < .007$), with both of these last two groups exhibiting a bisection point close to the geometric mean (9.67 vs. 9.46, $p > .05$). In addition, for time, the bisection point (BP = 10.56) was close to the arithmetic mean (AM) of the two anchor stimulus values (AM = 10.5). This is consistent with the results obtained in most temporal bisection studies in human adults and children (e.g., Droit-Volet & Rattat, 2007; Wearden, 1991; Wearden, Rogers, & Thomas, 1997a; Wearden, Wearden, & Rabbitt, 1997b), although some exceptions have been observed (Allan & Gibbon, 1991). For both number (BP = 9.32) and length (BP = 9.62), the bisection point was closer to the geometric mean (GM = 9.49). The bisection point was thus significantly shifted toward the right for time compared to number or length (Scheffé test, both $p < .002$), whereas it was equivalent in these last two conditions ($p > .05$).

As might well be expected, the ANOVA on the bisection point also revealed a significant main effect of the range of stimulus values, $F(1, 202) = 1{,}120.43$, $p < .0001$, thus indicating a higher bisection point value for the 8/20 pair than for the 4/10 pair (13.06 vs. 6.50). However, when the bisection points were plotted on the same relative scale by dividing the bisection points by the mean of the two anchor stimulus values (14 vs. 7), the bisection point values were identical (0.93).

The present experiment revealed similar age-related changes in bisection behaviour whatever the quantities presented—time, number, or line length—the discrimination sensitivity being lower and the bisection point higher in the younger children than in the 8-year-olds or the adults. Furthermore, in all age groups, but especially in the 5-year-olds, the psychophysical functions for time differed from those for either number or length, whereas the functions for number and length were equivalent. The following experiment tested whether the differences between the psychophysical functions for time and the other quantities would be observed if the presentation of number and line length values were sequential. Sequential presentation requires the attentive dynamic processing of the accumulated information in the same way as for the processing of duration.

EXPERIMENT 2

Method

Participants

The sample consisted of 206 new participants: 61 five-year-olds (30 girls and 31 boys, mean age = 5.03, $SD = 0.30$); 70 eight-year-olds (35 girls and 35 boys, mean age = 8.00, $SD = 0.39$); and 75 adults (68 women and 7 men, mean age = 19.33, $SD = 1.54$). As in Experiment 1, the children were recruited from nursery and primary schools, and the adults were students, all in Clermont-Ferrand.

Materials and procedure

The materials and the procedure used in Experiment 2 were similar to those used in Experiment 1, except for the stimuli and their sequential presentation. For the time bisection condition, the stimulus was a sequence of blue circles. The participants were told to evaluate the total duration of this sequence. The trial sequence was composed of a number of circles randomly chosen between 5, 7, and 9 for the 4/10-s anchor durations, and between 10, 14, and 18 for the 8/20-s anchor durations. The onset and the offset of a blue circle marked the beginning and the end of the sequence, respectively. The intercircle interval within a sequence was also randomly chosen between 100 and 2,000 ms. For the number bisection condition, the stimulus was a sequence of patterns, each of which was made up of a number of circles. The number of patterns, and the number of circles in each of those patterns, varied as a function of the stimulus value to be judged (see procedure in Experiment 1). For example, a sequence of circles representing the number 4 could consist of two successive patterns, one with 1 circle and the other with 3 circles. Similarly, a sequence of circles representing the number 10 could consist of five patterns with 2, 1, 4, 1, and 2 circles, respectively. The number of circles per pattern and the number of patterns per sequence were randomly determined. The duration of the presentation of each pattern and the interpattern interval were also randomly chosen between 400 and 1,200 ms. The participants were thus instructed to judge the total number of circles perceived in the sequence. For the length bisection condition, the stimulus was a sequence of lines (see procedure in Experiment 1), the total length of which had to be judged. Each sequence consisted of a random number of lines whose length also varied randomly. For example, a sequence of 4 cm could consist of four lines of 0.5, 1.5, 1.5, and 0.5 cm, respectively, and a longer sequence of 10 cm of three lines of 1, 5, and 4 cm. Thus, Experiment 2 presented the number and the length sequentially so that the total number and length required an accumulation across stimuli.

Results and discussion

Table 3 shows the number of training blocks required to obtain a successful trial block (i.e., 8 correct responses out of 8), thus allowing the participants to begin the bisection test. In line with the results of Experiment 1, there was no effect of stimulus range, $U = 4{,}959$, $p > .05$, and this was verified in all age and modality groups (all $p > .05$). However, the effect of age reached significance, $\chi^2(2) = 14.73$, $p > .002$, indicating that the 5-year-olds required more training blocks to learn to discriminate between the two standards than did the 8-year-olds, $U = 1{,}713$, $p < .005$, and the adults, $U = 1{,}784$, $p < .002$, whereas the number of training blocks required was similar for the two older age groups, $U = 2{,}570$, $p > .05$. The effect of modality did not reach significance, $\chi^2(2) = 97.14$, $p > .10$. Indeed, when each age group was considered separately, there were no between-modality differences in the number of training blocks required in the 5- and the 8-year-olds (both $p > .05$), but the adults needed a significantly greater number of training blocks in the length than in the number condition, $U = 240$, $p < .04$.

Figure 3 presents the psychophysical functions obtained from each modality when the stimulus

Table 3. *Number of training blocks required by each age group to meet the learning criterion in the training phase for the two stimulus ranges in each modality bisection when the stimuli were presented sequentially*

		Age group								
		5 years			*8 years*			*Adults*		
Modality	*Stimulus range*	*M*	*Min*	*Max*	*M*	*Min*	*Max*	*M*	*Min*	*Max*
Time	4–10 s	1.22	1	2	1.00	1	1	1.14	1	2
	8–20 s	1.14	1	2	1.08	1	2	1.00	1	1
Number	4–10	1.42	1	3	1.08	1	2	1.00	1	1
	8–20	1.85	1	4	1.23	1	2	1.00	1	1
Length	4–10 cm	1.20	1	2	1.20	1	3	1.00	1	1
	8–20 cm	1.20	1	2	1.09	1	2	1.33	1	2

Note: M = Mean. Min = minimum, Max = maximum number of training blocks.

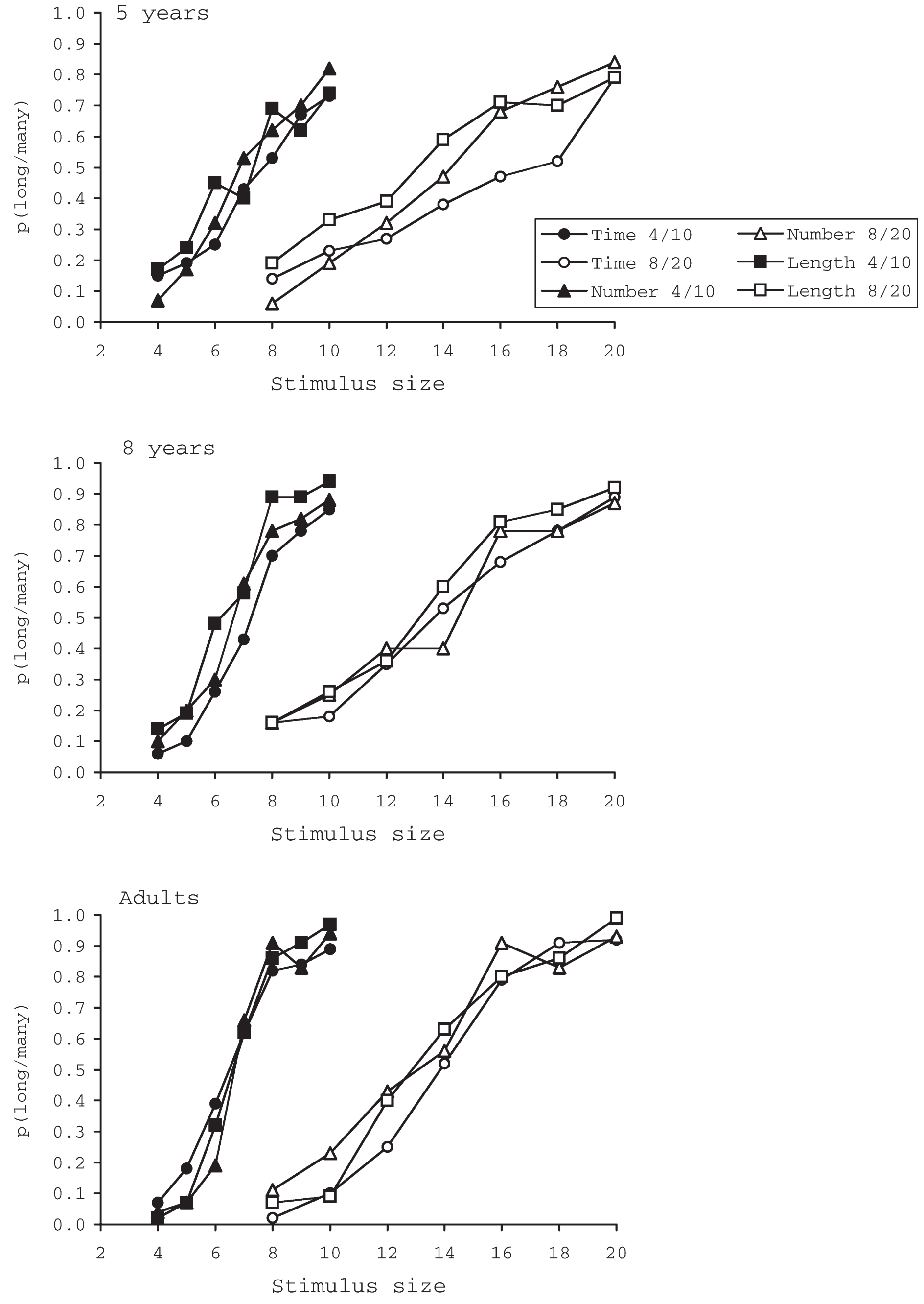

Figure 3. *Mean proportion of "long/many" responses plotted against probe stimulus when the stimuli were presented sequentially in each modality, for the 4/10 and the 8/20 ranges in the 5-year-olds, the 8-year-olds, and the adults.*

was presented sequentially, for both the 4/10 and the 8/20 stimulus ranges. It can be seen that there was no longer any clear difference between the slopes of the psychophysical functions for time and those for numerosity and length as the following statistical analyses indicate.

Weber ratio

The overall ANOVA (see Footnote 1) conducted on the individual Weber ratio (Table 4), calculated as in Experiment 1, showed a significant effect of age, $F(2, 183) = 32.50$, $p < .001$, and of modality, $F(2, 183) = 4.36$, $p < .02$, and a significant Age × Modality interaction, $F(4, 183) = 6.34$, $p < .03$. The comparison of modalities in each age group with the post hoc Scheffé tests revealed that in the 8-year-olds, as well as in the adults, the Weber ratios were close in the three modalities, time, number, and length (8-year-olds: .27 vs. .26 vs. .26; adults: .19 vs. .19 vs. .15, all $p > .05$). The 5-year-olds also obtained similar Weber ratios for time (.37) and length (.36; $p > .05$). However, in the 5-year-olds, when the stimulus was presented sequentially, the Weber ratio for number (.22) remained significantly lower than the corresponding ratios for time or length (both, $p < .007$), thus indicating that numerical sensitivity was higher than temporal and spatial sensitivity. The comparisons between the different age groups with the Scheffé test in each modality also revealed that, in the number condition, there was no significant difference in the Weber ratio value observed for the 5-year-olds, the 8-year-olds, and the adults (all $p > .05$). In contrast, the Weber ratio was higher in the 5-year-olds than in both the 8-year-olds and the adults for time (both $p < .03$) and for length (both $p < .$ 01). Thus, the age-related difference in bisection sensitivity appeared to be greater when it was time and length rather than number that had to be discriminated.

The overall ANOVA run on the Weber ratio also showed a significant main effect of stimulus range, $F(1, 183) = 9.66$, $p < .003$, but this factor did not significantly interact with any other factor: Range × Age, $F(2, 183) = 0.14$; Range × Modality, $F(2, 183) = 1.73$; Range × Modality × Age, $F(4, 183) = 1.13$, all $p > .05$. This seems to indicate that the Weber ratio value was not constant but varied with the stimulus magnitude. This would represent a violation of the scalar property of variance. As we were somewhat surprised by these findings, which were not consistent with those reported for Experiment 1 and those found in the studies with animals (see Fetterman, 2006), we decided a posteriori to test the conformity of the bisection behaviour to the scalar property for each modality. The statistical t test revealed that the Weber ratio did not significantly differ between the 4/10 and the 8/20 stimulus range for time (.26 vs. .26), $t(64) = 0.23$, $p > .05$, or for length (.23 vs. .27),

Table 4. *Means and standard deviations of Weber ratios and bisection points obtained in each age group in the different bisection conditions when the stimuli were presented sequentially*

		Age group					
		5 years		*8 years*		*Adults*	
Modality	*Stimulus range*	*WR*	*BP*	*WR*	*BP*	*WR*	*BP*
Time	4–10 s	.35 (.19)	7.86	.23 (.04)	7.33	.21 (.10)	6.70
	8–20 s	.40 (.21)	16.25	.29 (.08)	13.88	.17 (.08)	13.91
Number	4–10 n	.19 (.02)	6.74	.23 (.08)	6.84	.14 (.07)	6.74
	8–20 n	.25 (.09)	14.45	.30 (.08)	13.87	.24 (.06)	13.02
Length	4–10 cm	.34 (.14)	7.49	.25 (.10)	6.38	.13 (.05)	6.68
	8–20 cm	.39 (.16)	13.50	.27 (.13)	12.88	.17 (.05)	13.16

Note: WR = Weber ratios; BP = bisection points. Arithmetic mean = 7 and 14 for the 4–10 and the 8–20 pair, respectively, and geometric mean = 6.32 and 12.65. Standard deviations in parentheses.

$t(61) = 0.99, p > .05$. It was only with the sequential presentation of numerical magnitude that the Weber ratio value was significantly greater for the 8/20 than for the 4/10 stimulus range (27 vs. .19), $t(70) = 4.45, p < .001$.

Figure 4 indicates, for each modality, how the scalar property is manifested in the bisection functions, by showing the superimposition between the 4/10 and the 8/20 bisection functions when plotted on the same relative scale. An examination of Figure 4 seems to suggest that the superposition holds for both time and length, a result that is consistent with the principles of scalar discrimination. Surprisingly, for number, the superposition was almost perfect in the 5-year-olds. Contrary to the case in these young children, the superposition was not good in the adults, thus suggesting that the amount of variability in discriminates was relatively greater for the long than for the short values, thus causing discrimination behaviour to deviate from the scalar property of variance.

Bisection point

The ANOVA (see Footnote 1) conducted on the individual bisection points with age, modality and stimulus range as between-subject factors did not reveal any significant interaction between these three factors. Only the effects of the main factors reached significance. The significant main effect of range, $F(1, 187) = 1320.22, p < .0001$, indicated that the bisection point was higher for the 8/20 than for the 4/10 stimulus range (13.79 vs. 6.93). However, when we divided each bisection point by the mean of the two anchor stimulus values appropriate for each group tested, we obtained the same bisection point value (i.e., 0.99). The significant main effect of age $F(2, 187) = 10.28, p < .0001$, was due to the bisection point value significantly higher in the 5-year-olds than in the adults (Scheffé post hoc test, $p < .0001$). The most interesting result here was the main effect of modality, $F(2, 187) = 10.28$, $p < .0001$. In Experiment 2, with the sequential presentation of stimuli, the bisection point was closer to the arithmetic mean of the two anchor stimulus values (AM = 10.5) than to their geometric mean (GM = 9.48) for each modality—that is, for time (BP = 10.80), number (BP = 10.33), and length (BP = 10.09) alike. Furthermore, the bisection points were now similar for the three different modalities ($p > .05$), except for the difference between time and length, which reached significance ($p < .01$). As discussed below, this suggests that the fact that the bisection point was located close to the arithmetic mean was in part due to the sequential presentation of the quantities.

In Experiment 2, we changed the manner of presentation for number and length from simultaneous to sequential presentation. Our results suggested that this change was responsible for the Weber ratios observed for number and length, which were equivalent to those observed for time. In order to examine whether the data from the sequential presentation for number and length in Experiment 2 effectively differed from those from the simultaneous presentation in Experiment 1, we conducted a cross-experimental comparison of the data from these conditions. The overall ANOVA conducted on the Weber ratio with the experiment as between-subjects factor found a significant Experiment × Age, $F(2, 384) = 3.14, p < .05$, Experiment × Modality, $F(2, 384) = 20.72, p < .0001$, and Experiment × Modality × Age interaction, $F(4, 384) = 6.36, p < .0001$, with a main effect of experiment, $F(1, 384) = 143.66, p < .0001$, and of modality, $F(2, 384) = 42.15, p < .0001$. There was no other significant interaction involving the experiment factor, and the other effects replicated those found in Experiments 1 and 2. As expected, there was no difference in sensitivity to time between the nonsequential and the sequential presentation: Weber ratio: 5 years, $t(32) = 1.30$; 8 years, $t(47) = .81$; adult, $t(55) = 0.99$; all $p > .05$. By contrast, the sensitivity to number and to length was significantly different between the stimulus presentation modes: number: 8 years, $t(49) = 6.55$; adults, $t(46) = 5.62$; both $p < .05$; length: 5 years, $t(40) = 6.18$; 8 years, $t(40) = 7.28$; adults, $t(46) = 6.57$; all $p < .05$. Except for the number in the 5-year-olds, the experiment difference just failed to reach significance, $t(47) = 1.85, p = .07$. The ANOVA conducted on the bisection point found also a main effect of experiment, $F(1, 389) = 20.70, p < .0001$, but there was no significant interaction involving the experiment factor.

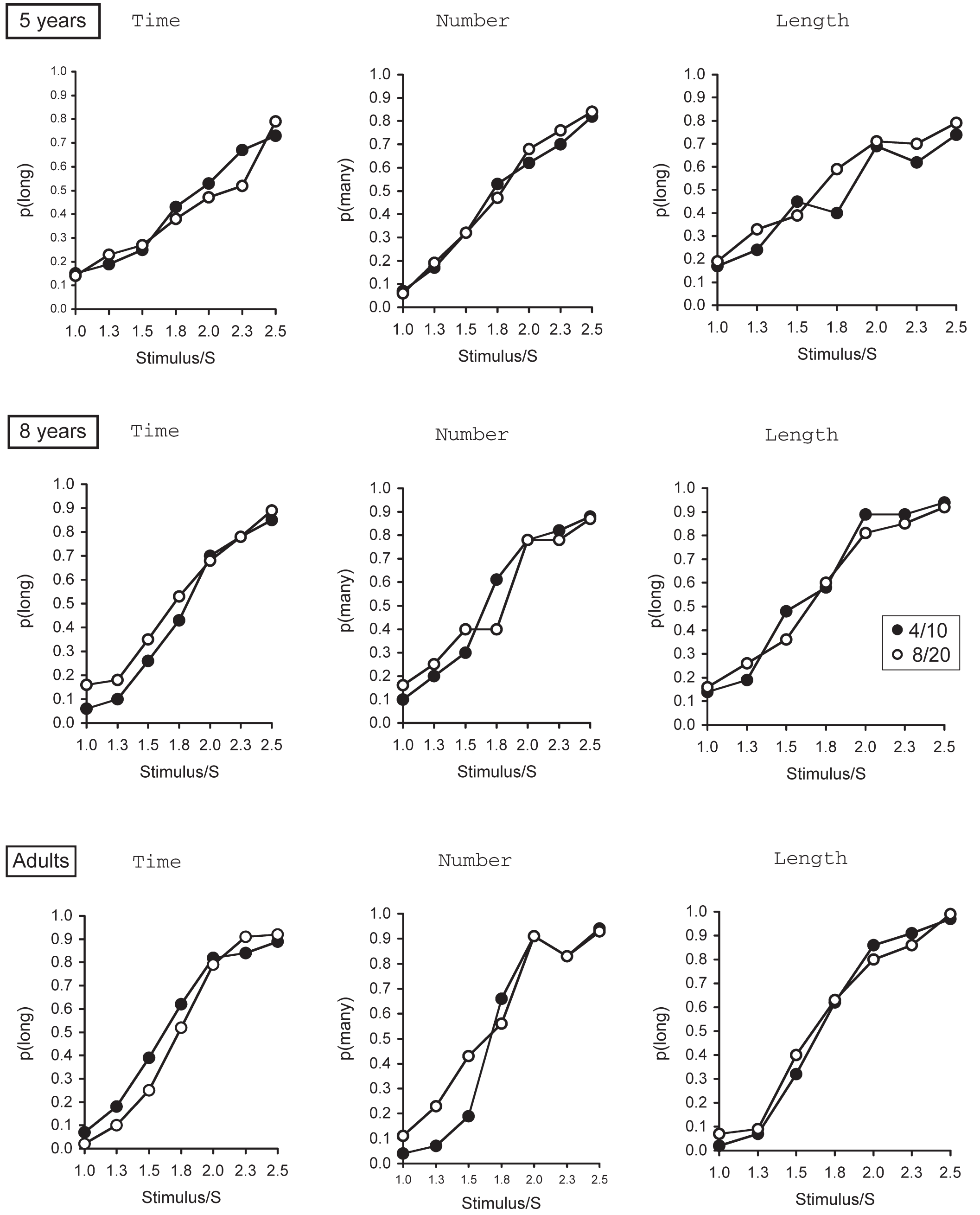

Figure 4. *Psychophysical functions for the three age groups plotted against probe stimulus divided by the shortest stimulus value when the stimuli were presented sequentially for the 4/10 and the 8/20 ranges for time (left panel), number (middle panel), and length (right panel).*

Consequently, the bisection point was lower in the nonsequential (9.44) than in the sequential presentation of stimuli (10.41). In sum, Experiment 2 showed that presenting number and length sequentially tended to increase the similarities in the sensitivity to the dimensions of time, number, and line length. Furthermore, it is important to note that the Weber ratio values (Table 4) for time, length, and number obtained in Experiment 2 were similar to that found for time in Experiment 1 (Table 2). This demonstrated that duration is "naturally" sequential, as discussed below.

GENERAL DISCUSSION

The present study examined the psychophysical functions in a bisection task and their age-related changes for three different quantities (time, number, and length) when presented sequentially or nonsequentially. In each condition, the bisection behaviour conformed well to the scalar property of variance. Indeed, whatever the quantity tested, the Weber ratio remained constant as the stimulus value increased, and it did so with both the nonsequentially presented stimuli and the sequentially presented stimuli, except in the adults when the number was presented sequentially. Furthermore, our studies showed that this scalar property of variance, which was obtained for each type of discriminated quantity, was observed in children as young as 5 years old and persisted across the different age groups tested. These results are consistent with those found in developmental studies concerning both time (Droit-Volet, 2001, 2002; Droit-Volet & Wearden, 2001) and number discrimination (Mix, Huttenlocher, & Levine, 2002; Xu, 2003; Xu & Spelke, 2000). The fundamental property of scalar variance therefore appears not to be specific to one dimension, such as time, but general to all the quantities, whether continuous or not. This supports the idea that all quantities are represented by analogue magnitudes with a scalar variability, and this from an early age (Gallistel & Gelman, 2000).

However, our data suggest that the scalar property is not observed in discrimination behaviour when number is presented sequentially, especially in the case of adults. Indeed, we appeared to observe relatively less variability in judgements for the 4/10 than for the 8/20 values. This is not consistent with the results previously obtained in animal-based studies (e.g., Church & Meck, 1984; Fetterman, 1993; Fetterman & Killeen, 1992). It could be suggested that our findings were due to a subitizing mechanism. The subitizing refers to the rapid, accurate, and confident judgements of number performed for small numbers of items (<4; Deheane, 1997; Kaufman, Lord, Reese, & Volkmann, 1949). In our sequential presentation of the number, a small number of stimuli (circles) were effectively presented step by step (i.e., sequence of patterns, each of which were made up of a small number of circles). Furthermore, in their experiment, Meck and Church (1983) have used a constant rate of stimulus presentation, one per second. In our study, both the duration of the presentation of each pattern of stimuli and the interpattern interval were randomly chosen between 400 and 1,200 ms. This rhythm of stimuli presentation might make the counting of pulses by an internal accumulator process more variable, in particular when large quantities of stimuli are involved.

Our data revealed that, for the nonsequential presentation of stimuli, the psychophysical functions in a bisection task were very similar for number and length with both having the same Weber ratio values and the same bisection points—that is, close to the geometric mean of the two anchor stimuli. These data are entirely consistent with those found in the magnitude or parity tasks that have compared numerosity and space judgements (Hubbard et al., 2005). However, the real originality of our study was to show that, although duration is also a magnitude, the psychophysical functions for time clearly differed from those for the other quantities (number and length), and this in all age groups (Experiment 1). Indeed, the Weber ratio was higher for time than for number and line length, thus indicating a lower sensitivity to the former.

The bisection point value was also larger for time than for both number and length—that is, closer to the arithmetic than to the geometric mean of the two anchor stimuli. However, in Experiment 2, when time, number, and length were presented sequentially, the psychophysical functions for all the quantities superimposed well. Furthermore, for both number and length, we found the same Weber ratio and bisection point values as those for time. In other words, the difference in the discrimination judgements between time and the other dimensions disappeared when they shared the same characteristic with time—that is, a sequential flow of information.

Although it is difficult to draw any conclusion with behavioural studies showing the same sensitivity to different quantities, our results allow us to assume that there should be equivalences in the mental representations for all the quantities. However, we might suppose that the mode of presentation of these quantities—that is, whether sequential or not—determines whether or not an additional cognitive operation is required. When the quantity is presented sequentially, this operation would be related to the dynamic accumulation process. Consequently, this operation would always be required for the processing of time, and only for that of the other quantities when they are presented sequentially. As stated in the Introduction, the timing models (Church & Meck, 1984; Gibbon, 1977) proposed an internal clock system that made it possible to accurately measure the passage of time by means of the accumulation of neural pulses. Subsequently, Meck and Church (1983) extended this timing model to incorporate discriminations of another discontinuous quantity (i.e., numerosity) and proposed a switch system that is flexible in the way that the pulses are gated. Regardless of our results, it would appear to be necessary to try to extend this model to a continuous quantity such as length when presented sequentially. However, if such a model is able to account for all sequentially presented quantities then we must ask whether the model is specific to timing or whether it is a general model that accounts for the accumulator processes (Brown et al., 2005) and is consequently well adapted to the processing of temporal information given that time is naturally sequential.

Our findings thus support the idea that the fundamental capacities for the processing of all quantities, whatever form they take, emerge early (Brannon & Roitman, 2003), although the discrimination of analogue magnitudes improves with age. Finally, it appears to be the cognitive monitoring of the flow of information in a sequence of events that is, relatively speaking, more subject to age-related changes because it is dependent on the development of attentional capacities or the ability to maintain information in working memory (Droit-Volet et al., 2007b). It is now firmly established that time processing is particularly attention demanding (Coull et al., 2004). Indeed, the processing of duration requires participants to focus attention in good time in order to capture the beginning of the stimulus to be timed and then to keep this attention focused on the duration until it ends. Using a signal indicating the arrival of a visual stimulus to be timed, Droit-Volet (2003) has demonstrated that young children's orientation of attention on the onset of the to-be-timed stimulus is more variable than that of their older counterparts. Other studies using a distractor (Droit-Volet et al., 2006; Gautier & Droit-Volet, 2002b; Zakay, 1992) or a discontinuous duration (Droit-Volet & Clément, 2005) have also revealed that young children's attention is more easily distracted from the processing of time. Consequently, children's difficulty in attending to time and keeping their attention focused would produce a greater amount of noise in time encoding and/or sometimes an attention-related shortening effect (Gautier & Droit-Volet, 2002a). This latter attention-related effect would be consistent with our results, which indicate a significant shifting of the bisection point toward the right for time and the other sequentially presented dimensions compared to the simultaneous presentation of number or length. However, decisional processes may also be involved in the changes in discriminative judgements as a function of the type of quantity. Whatever the case, we may assume that the attention or working-memory-based processing of the flow of information is not specific to time but is common to all sequentially presented quantities.

When all the quantities were presented sequentially, the bisection task produced very similar psychophysical functions in both the 8-year-olds and the adults. Unlike the 8-year-olds and the adults, the youngest children exhibited greater sensitivity to number than to time or length. A greater sensitivity to numerosity than to time has also been found in studies using a sequence of stimuli in which time was confounded with number (Droit-Volet et al., 2003; Roitman et al., 2007). This has been explained in terms of the representation of number, which is accessed more automatically than the representations of length and of time. This might suggest that, in a sequence of stimuli, the evaluation of discontinuous quantities is less attention demanding than that of continuous quantities—that is, time or length.

Up to now, the clear consensus has been that the processing of time involves a specialized temporal internal-clock system. However, and particularly interesting for a new line of research, our study provides a body of empirical data in support of the idea that the bisection discrimination of all quantities obeys the same laws and perhaps shares a common mechanism. The idea of a common mechanism has already been suggested for space and number, on one hand, and for number and time, on the other. Our studies comparing three different dimensions have filled the gap by linking space, number, and time. In line with Walsh (2003a, 2003b), we might thus suppose that time, space, and number are all components of a generalized magnitude system, operating from birth. However, because time is naturally sequential (i.e., a stimulus extends as time progresses), its processing would require additional dynamic cognitive control, which involves both attention and working-memory processes (Lewis & Miall, 2006; Staddon, 2005). This helps us to explain the results of previous studies that suggest that the consciousness of time in young children derives from experienced events, with there being an initial confusion between time and the other dimensions, such as movement or the force in action, in accordance with the rule "more . . . equals more time" (e.g., Droit-Volet, 1998, Droit-Volet & Rattat, 1999; Levin, 1992; Piaget, 1946). As Gibson (1975) said, events are perceivable, but time is not.

Original manuscript received 14 November 2006
Accepted revision received 28 September 2007

REFERENCES

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

Balci, F., & Gallistel, C. R. (2006). Cross-domain transfer of quantitative discriminations: Is it all a matter of proportion? *Psychonomic Bulletin and Review*, *13*, 636–642.

Brannon, E., & Roitman, J. (2003). Nonverbal representations of time and number in animals and human infants. In W. Meck (Ed.), *Functional and neural mechanisms of interval timing*. Boca Raton, FL: CRC Press.

Brannon, E., Roussel, L., & Meck, W. (2004). Timing in the baby brain. *Brain Research*, *21*, 227–233.

Breukelaar, J., & Dalrymple-Alford, J. (1998). Timing ability and numerical competence in rats. *Journal of Experimental Psychology: Animal Behavior Processes*, *24*, 84–97.

Brown, G. D. A., McCormack, T., Smith, M., & Stewart, N. (2005). Identification and bisection of temporal durations and tone frequencies: Common models for temporal and non-temporal stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 919–938.

Church, R., & Deluty, M. (1977). Bisection of temporal intervals. *Journal of Experimental Psychology: Animal Behavior Processes*, *3*, 216–228.

Church, R., & Meck, W. (1984). The numerical attribute of stimuli. In H. C. Roitblat, T. G. Bever, & H. S. Terrace (Eds.), *Animal cognition*. Hove, UK: Lawrence Erlbaum Associates Ltd.

Clément, A., & Droit-Volet, S. (2006). Counting in a temporal discrimination task in children and adults. *Behavioural Processes*, *71*, 164–171.

Colombo, J., & Richman, W. (2002). Infant time keeping: Attention and temporal estimation in 4-month-olds. *Research Report*, *13*, 475–479.

Coull, J. (2004). fMRI studies of temporal attention: Allocating attention within or towards, time. *Cognitive Brain Research*, *21*, 216–226.

Coull, J., Vidal, F., Nazarian, B., & Macar, F. (2004). Functional anatomy of the attentional modulation of time estimation. *Science*, *303*, 1506–1508.

Dehaene, S. (1997). *The number sense: How the mind creates mathematics*. New York: Oxford University Press.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology*, *20*, 487–506.

Delgado, M. de L., & Droit-Volet, S. (2007). Testing the representation of time in reference memory in the bisection and the generalization task: The utility of a developmental approach. *Quarterly Journal of Experimental Psychology*, *60*, 820–836.

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. (2002). Scalar timing in temporal generalization in children with short and long stimulus durations. *Quarterly Journal of Experimental Psychology*, *55A*, 1193–1209.

Droit-Volet, S. (2003). Alerting attention and time perception in children. *Journal of Experimental Child Psychology*, *85*, 372–384.

Droit-Volet, S., & Clément, A. (2005). Time perception in children and adults: Effects of continuous and discontinuous signal. *Current Psychology of Cognition*, *23*, 229–248.

Droit-Volet, S., Clément, A., & Fayol, J. (2003). Timing and number discrimination in a bisection task with a sequence of stimuli: A developmental approach. *Journal of Experimental Child Psychology*, *84*, 63–76.

Droit-Volet, S., Clément, A., & Wearden, J. (2001). Temporal generalization in children. *Journal of Experimental Child Psychology*, *80*, 271–288.

Droit-Volet, S., Delgado, M. de L., & Rattat, A. C. (2006). The development of the ability to judge time in children. In J. R. Marrow (Ed.), *Focus on child psychology research* (pp. 81–104). New York: Nova Science Publishers.

Droit-Volet, S., Meck, W., & Penney, T. (2007a). Sensory modality effect and time perception in children and adults. *Behavioural Processes*, *74*, 244–250.

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., & Rattat, A. C. (2007). A further analysis of temporal bisection behavior in children with and without reference memory: The similarity and the partition task. *Acta Psychologica*, *125*, 240–256.

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

Droit-Volet, S., Wearden, J., & Delgado-Yonger, M. (2007b). Short term memory for time in children and adults: A behavioral study and a model. *Journal of Experimental Child Psychology*, *2*, 223–237.

Fetterman, J. G. (1993). Numerosity discrimination: Both time and number matter. *Journal of Experimental Psychology: Animal Behavior Processes*, *19*, 149–164.

Fetterman, J. G. (2006). Time and number: Learning, psychophysics, stimulus control, and retention. In E. A. Wasserman & T. Zentall (Eds.), *In comparative cognition: Experimental explorations of animal intelligence* (pp. 285–304). Oxford University Press.

Fetterman, J. G., & Killeen, P. R. (1992). Time discrimination in Columba livia and Homo sapiens. *Journal of Experimental Psychology: Animal Behavior Processes*, *18*, 80–94.

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, P., & Orban, G. (2003). Parietal representation of symbolic and non-symbolic magnitude. *Journal of Cognitive Neurosciences*, *15*, 47–56.

Fortin, C., Bédard, M. C., & Champage, J. (2005). Timing during interruptions in timing. *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 276–288.

Fraisse, P. (1967). *Psychologie du temps* [Psychology of time]. Paris: PUF.

Gallistel, C., & Gelman, R. (2000). Non-verbal numerical cognition: From reals to integers. *Trends in Cognitive Sciences*, *4*, 59–65.

Gautier, T., & Droit-Volet, S. (2002a). Attention and time estimation in 5- and 8-year-old children: A dual-task procedure. *Behavioural Processes*, *58*, 56–66.

Gautier, T., & Droit-Volet, S. (2002b). The impact of attentional distraction on temporal bisection in children. *International Journal of Psychology*, *37*, 27–34.

Gibbon, J. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological Review*, *84*, 279–325.

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.

Gibson, J. J. (1975). Events are perceivable but time is not. In J. T. Fraser & N. Lawrence (Eds.), *The study of time II. Proceedings of the Second Conference of the International Society for the Study of Time*. Berlin: Springer-Verlag.

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews*, *6*, 435–447.

Kadosh, R. C., Henik, A., Rubinsten, O., Mohr, H., Dori, H., Van de Ven, V., et al. (2005). Are numbers special? The comparison systems of the human brain investigated by fMRI. *Neuropsychologia*, *43*, 1238–1248.

Kaufman, E. L., Lord, M. W., Reese, T. W., & Volkmann, J. (1949). The discrimination of visual number. *American Journal of Psychology*, *62*, 498–525.

Lejeune, H., & Wearden, J. (2006). Scalar properties in animal timing: Conformity and violations. *Quarterly Journal of Experimental Psychology*, *59*, 1875–1908.

Levin, I. (1992). The development of the concept of time in children: An integrative model. In F. Macar, V. Pouthas, & W. J. Friedman (Eds.), *Time, action and cognition: Towards bridging the gap* (pp. 13–33). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Lewis, P., & Miall, C. (2006). Remembering the time: A continuous clock. *Trends in Cognitive Sciences*, *10*, 9.

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

McCormack, T., Brown, G., Smith, M., & Brock, J. (2004). A timing-specific memory distortion effect in young children. *Journal of Experimental Child Psychology*, *87*, 33–56.

McCormack, T., Wearden, J. H., Smith, M. C., & Brown, G. D. A. (2005). Episodic temporal generalization: A developmental study. *Quarterly Journal of Experimental Psychology*, *58A*, 693–704.

Meck, W., & Church, R. (1983). A mode of control model of counting and timing processes. *Journal of Experimental Psychology: Animal Behavior Processes*, *9*, 320–334.

Meck, W., Church, R., & Gibbon, J. (1985). Temporal integration in duration and number discrimination. *Journal of Experimental Psychology: Animal Behavior Processes*, *4*, 591–597.

Mix, K., Huttenlocher, J., & Levine, S. (2002). Multiple cues for quantification in infancy: Is number one of them? *Psychological Bulletin*, *128*, 278–294.

Ornstein, R. (1969). *On the experience of time*. Harmondsworth, UK: Penguin.

Piaget, J. (1946). *Le développement de la notion de temps chez l'enfant*. [The development of the notion of time in children]. Paris: PUF.

Pinel, P., Piazza, M., Le Bihan, D., & Dehaene, S. (2004). Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. *Neuron*, *41*, 983–993.

Rattat, A.-C., & Droit-Volet, S. (2005). Development of long-term memory for duration in a temporal bisection task. *Quarterly Journal of Experimental Psychology*, *58B*, 163–176.

Roberts, W. A. (1995). Simultaneous numerical and temporal processing in the pigeon. *Current Directions in Psychological Science*, *4*, 47–51.

Roberts, W. A. (1997). Does a common mechanism account for timing and counting phenomena in the pigeon? In C. M. Bradshaw & E. Szabadi (Eds.), *Time and behavior: Psychological and neurobehavioural analyses* (pp. 185–215). Amsterdam: Elsevier Science.

Roberts, W. A., & Boisvert, M. (1998). Using the peak procedure to measure timing and counting processes in pigeons. *Journal of Experimental Psychology: Animal Behavior Processes*, *24*, 416–430.

Roberts, W. A., & Mitchell, S. (1994). Can a pigeon simultaneously process temporal and numerical information? *Journal of Experimental Psychology: Animal Behavior Processes*, *20*, 66–78.

Roitman, J. D., Brannon, E. M., Andrews, J. R., & Platt, M. L. (2007). Mental representation of time and number in adults. *Acta Psychologica*, *124*, 296–318.

Staddon, J. E. R. (2005). Interval timing: Memory, not a clock. *Trends in Cognitive Sciences*, *9*, 7.

Walsh, V. (2003a). Cognitive neuroscience: Numerate. *Current Biology*, *13*, 447–448.

Walsh, V. (2003b). Time: The back-door of perception. *Trends in Cognitive Sciences*, *7*, 335–338.

Wearden, J. (1991). Human performance on an analogue of an interval bisection task. *Quarterly Journal of Experimental Psychology*, *43B*, 59–81.

Wearden, J. H., & Bray, S. (2001). Scalar timing without reference memory? Episodic temporal generalization and bisection performance. *Quarterly Journal of Experimental Psychology*, *54B*, 289–309.

Wearden, J., & Ferrara, A. (1995). Stimulus spacing effects in temporal bisection by humans. *Quarterly Journal of Experimental Psychology*, *48B*, 289–310.

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

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

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

Xu, F. (2003). Numerosity discrimination in infants: Evidence for two systems of representations. *Cognition*, *89*, B15–B25.

Xu, F., & Spelke, E. (2000). Large number discrimination in 6-month-old infants. *Cognition*, *74*, B1–B11.

Zakay, D. (1992). The role of attention in children's time perception. *Journal of Experimental Child Psychology*, *54*, 355–371.