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Short-term memory for time in children and adults: A behavioral study and a model

Sylvie Droit-Volet [a,*], John Wearden [b], Maria Delgado-Yonger [a]

[a] *Laboratoire de Psychologie Sociale et Cognitive, CNRS (UMR 6024), Université Blaise Pascal, 63037 Clermont-Ferrand, France*
[b] *School of Psychology, Keele University, Keele, Staffordshire ST5 5BG, UK*

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Abstract

This experiment investigated the effect of the short-term retention of duration on temporal discrimination in 5- and 8-year-olds, as well as in adults, by using an episodic temporal generalization task. In each age group, the participants' task was to compare two successive durations (a standard and a comparison duration) separated by a retention interval of 500 ms, 5 s, or 10 s, with the order of presentation of these two durations being counterbalanced. The results revealed a shortening effect for the first presented stimulus in all of the age groups, although this was greater in the younger children, thereby indicating the presence of a negative time–order error. Furthermore, introducing a retention delay between the two durations did not produce a shortening effect but instead flattened the generalization gradient, especially in the younger children. However, this flattening of the generalization gradient with the retention delay was more marked between 500 ms and 5 s than between 5 s and 10 s. Thus, retaining the first duration in short-term memory during a task requiring the comparison of two successive durations reduced temporal discrimination accuracy and did so to a greater extent in the younger children.

Keywords: Time; Memory; Short-term memory; Children

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[*] Corresponding author. Fax: +33 4 73 40 64 82.
E-mail address: droit@srvpsy.univ-bpclermont.fr (S. Droit-Volet).

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Introduction

The past 10 years have seen an increase in the number of studies devoted to time estimation in 3- to 10-year-olds. Several of these studies have used the generalization task that initially was employed for animals and humans adults (Clément & Droit-Volet, 2006; Delgado & Droit-Volet, 2007; Droit-Volet, 2002; Droit-Volet, Clément, & Wearden, 2001; Droit-Volet & Izaute, 2005; McCormack, Brown, Maylor, Darby, & Green, 1999; McCormack, Brown, Smith, & Brock, 2004; McCormack, Wearden, Smith, & Brown, 2005). In this task, the participants are presented with a number of examples of a standard duration. They are then required to judge whether a series of comparison durations (shorter than, longer than, or equal to the standard) are equal in duration to the standard or not (indicated by "same" or "different" responses). In these studies, young children, like human adults, produce orderly generalization gradients with a proportion of same responses that peaks at the comparison duration value equal to the standard and declines as deviation from the standard increases. However, one major age-related change is an increase with age in the steepness of the generalization gradient, with the gradient being flatter in 3- and 5-year-olds than in older children. Thus, in the generalization task, younger children exhibit lower sensitivity to time than do older children. In addition, some studies have suggested a change with age in the distributional pattern of same responses around the standard, with the gradients being skewed to the left in 5- and 6-year-olds, symmetrical in 10-year-olds, and skewed to the right in adults (Clément & Droit-Volet, 2006; McCormack et al., 1999, 2004). However, this developmental trend from left to right asymmetry has not always been observed given that symmetrical gradients have also been obtained in 3- and 5-year-olds and right asymmetrical gradients have also been obtained in 8-year-olds (Delgado & Droit-Volet, 2007; Droit-Volet et al., 2001; Droit-Volet & Izaute, 2005). Thus, the main critical question is to identify what accounts for the flatter temporal generalization gradients in younger children.

According to the information processing models derived from scalar timing theory (Gibbon, 1977; Gibbon, Church, & Meck, 1984), subjective duration is represented by the quantity of pulses emitted by a pacemaker and stored in an accumulator during the stimulus that is to be judged (for a recent review see Buhusi & Meck, 2005). The temporal judgment depends on the comparison, via a decision mechanism, between the representation of the comparison duration stored in short-term memory and the representation of the standard duration stored in long-term memory. According to this model, as the duration is processed accurately, the main source of variability in temporal judgments would lie in the processes responsible for the storage of the standard duration in long-term memory. Using a scalar timing-based model, Droit-Volet and colleagues (2001) showed that young children's poorer performance on the generalization task is due to their more variable representation of the standard duration in long-term memory. However, in a recent study, Delgado and Droit-Volet (2007) directly manipulated the amount of noise in the samples of the standard duration and demonstrated that the noisier long-term memory representation of the standard in children results not from long-term storage processes but rather from the initial encoding of time and also probably from the short-term retention of time.

In their model, which is slightly different from that proposed by scalar timing theory, McCormack and colleagues (1999) assumed that the main source of errors in time discrimination in children probably lies in the perception of to-be-judged comparison duration.

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Working within this perspective, McCormack and colleagues (2005) recently suppressed the representation of the standard duration in long-term memory by using the episodic temporal generalization task developed by Wearden and Bray (2001). In this task, two successive durations were presented on each trial, and participants needed to judge whether or not they were equal. To prevent the participants from forming a long-term memory of the standard, the standard was changed from trial to trial and the comparison durations were certain ratios of the standard (e.g., <1.0 [shorter], 1.0 [equal], or >1.0 [longer]). In this new experimental condition, the developmental changes in the generalization performance mirrored those observed in the classical version of the generalization task described above, which is proposed to involve reference memory of the standards. Therefore, McCormack and colleagues (2005) concluded that the main source of developmental changes in temporal discrimination performance lies in the ‘‘perceptual changes’’ of time rather that in the long-term representation of the standard. However, they added that ‘‘it remains to be established exactly which aspects of the set of processes that we have categorized as perceptual change developmentally’’ (p. 702).

Most studies of time judgments have emphasized the role of the development of attention in the processing of time (for a review, see Droit-Volet, Delgado, & Rattat, 2006) rather than the development of ability to keep duration on-line in short-term memory, although the two may well be related (Cowan, 2001). According to Baddeley and Hitch’s (1974) model, working memory holds a limited amount of information for a limited period of time, namely 2 s (for a recent review, see Baddeley, 2003). As we further explain in the discussion, strong evidence exists that performance on short-term memory tasks improves throughout childhood, reaching adult levels of performance by approximately 14 or 15 years of age (Cowan, 1997; Cowan et al., 2003; Gathercole, Pickering, Ambridge, & Wearing, 2004; Pickering, 2001). Consequently, the purpose of the current study was to test the effect of the short-term retention interval on time discrimination and the associated developmental changes in children by using McCormack and colleagues’ episodic temporal generalization procedure, into which we introduced a retention interval between the two successive durations to be compared.

To date, no research has been published into how the retention of duration in short-term memory may affect children’s perception of time. However, short-term retention for duration has been studied extensively in animals by Spetch and colleagues (Grant & Spetch, 1993; Santi, Weise, & Kuiper, 1995; Spetch, 1987; Spetch & Grant, 1993; Spetch & Wilkie, 1983). Pigeons initially were trained to make one response after a short (e.g., 2-s) stimulus presentation and another after a longer (e.g., 10-s) stimulus, with the response keys being made available immediately after stimulus offset. Then testing ensued with a retention interval (5–20 s) between the signal offset and the participant’s opportunity to make a response (i.e., a delayed matching-to-sample procedure), and there was a decline in performance accuracy as the retention interval increased. Furthermore, with increasing delay, a ‘‘choose short effect’’ appeared, with the participants responding short more often (i.e., pecking the key associated with the response reinforced after the short stimulus duration used in training). Thus, as demonstrated previously by Church (1980), when the retention interval increases, the duration of a stimulus retained in memory seems to shorten. Based on the idea of an analogue representation of time in the form of a quantity of pulses, Spetch and Wilkie (1983) proposed that the duration decay results in a loss of pulses during the retention interval, leading to ‘‘subjective shortening’’ of the duration retained in memory.

Wearden and Ferrara (1993) and Wearden et al. (2002) investigated subjective shortening in human adults with a procedure in which a retention delay (usually 1, 2, 5, or 10 s) was introduced between the two durations to be compared. They obtained a subjective shortening effect with auditory and visual stimuli, but this was mixed with a negative time–order error in some cases. Time–order errors (for a review, see Hellström, 1985) are defined as differences in judgments of successive stimuli that depend on presentation order. For example, if we need to judge which is the louder of two stimuli, A and B, time–order errors are manifest if the judgments coming from order AB and order BA are not the same. In general, a positive time–order error usually is defined as a tendency to judge that the second stimulus is smaller in magnitude, whereas a negative time–order error is a tendency to judge that the first stimulus is smaller. Thus, it may appear difficult in the results to distinguish the shortening effect due to the short-term retention of the durations from that due to a negative time–order error. However, as explained later, counterbalancing the order between the standard duration and the comparison duration would facilitate this distinction.

The current experiment investigated the effect of a retention interval on generalization gradients in 5- and 8-year-olds, as well as in adults, using an episodic generalization task with two successive durations (a standard and a comparison duration) on each trial. Unlike a number of other studies that either avoid or neglect the time–order error effect phenomenon, the order of presentation of the standard and comparison stimuli was counterbalanced across groups, so that the direction of any time–order error, if present, could be readily observed. Our main hypothesis was that temporal discrimination accuracy would decrease with increased retention interval between the first and second stimuli presented on each trial, thereby flattening the generalization gradient, and that this effect would decrease with age. According to the work conducted by Spetch and colleagues, the subjective duration of the first stimulus would also shorten with increases in the retention interval, and this might be particularly so in the younger children who have limited short-term memory capacities.

Method

Participants

The sample consisted of 270 participants: 90 5-year-olds (41 girls and 49 boys, mean age = 5.09 years, *SD* = 0.59), 90 8-year-olds (44 girls and 46 boys, mean age = 7.91 years, *SD* = 0.54), and 90 adults (77 women and 13 men, mean age = 20.03 years, *SD* = 2.66). The children were recruited from nursery and primary schools with parental consent, and the adults were first-year psychology students from Blaise Pascal University, all in Clermont-Ferrand, France.

Materials

The participants were tested individually in a quiet room in their school in the case of the children and in the psychology department in the case of the adults. They were seated in front of an Apple Macintosh computer, which controlled the experiment and recorded the data via PsyScope. The stimulus, the duration of which varied, was a blue circle of

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4.5 cm in diameter presented in the center of the computer screen. The participants responded to the stimulus by pressing the K and D keys on the computer keyboard.

Procedure

The participants were presented with two successive stimulus durations: one for the standard duration (*s*) and the other for the comparison duration (*c*). On each trial, the standard duration was randomly chosen between 1200 and 2000 ms. Each comparison duration had a ratio of 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, or 1.75 to the standard.

To investigate any possible time–order error effect, the participants in each age group were assigned to one of the two groups as a function of the order of presentation of the stimulus durations. In the *s–c* groups, the first stimulus duration was the standard duration (*s*), and the second stimulus duration was the comparison duration (*c*). In the *c–s* groups, the order was reversed. Furthermore, in each group (i.e., *s–c* and *c–s*), the participants were assigned to one of the three subgroups as a function of the delay between the two stimulus durations, and a delay of 500 ms, 5 s, or 10 s was used. This resulted in 18 groups, 3 (Age) × 3 (Interval Retention) × 2 (Stimulus Duration Order), with 15 participants per group.

In all of the groups, the participants' task was to judge whether the second stimulus duration was identical to the first one. The participants pressed one computer key if they judged that the second stimulus duration was identical to the first one (same responses) and pressed another key if they judged that the second stimulus duration was not identical to the first one. The key press assignment was counterbalanced. The participants were given 10 blocks of nine trials each; in each block, they were given three trials with the 1.00 ratio and six trials with the other ratios (one trial with each of 0.25, 0.50, 0.75, 1.25, 1.50, and 1.75). The intertrial interval value was also randomly chosen among the values between 1 and 3 s. The 10 blocks were divided into two series of 5 blocks separated by a 5-min break. The trials were presented in a random order within each block.

Results

Generalization gradients

Fig. 1 shows the proportion of same responses plotted against the ratios (i.e., comparison durations) for each retention delay when the standard was presented first (*s–c*, left panels) and second (*c–s*, right panels) for the 5-year-olds, the 8-year-olds, and the adults. An earlier analysis of variance (ANOVA) on the proportion of same responses did not find any sex or key press order effects, nor did it find any interactions involving these two factors. Therefore, we excluded these two factors from the subsequent statistical analyses. Thus, the overall ANOVA was run with three between-subject factors (Age: 5 years, 8 years, or adults; Retention Delay: 500 ms, 5 s, or 10 s; and Stimulus Duration Order: *s–c* or *c–s*) and one within-subject factor (Comparison Duration: 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, or 1.75). Because there is some evidence of departure from the sphericity assumption, the ANOVA used the Greenhouse–Geisser correction. This ANOVA found a significant main effect of age, $F(2,252) = 7.32$, $p < .05$, and of comparison duration, $F(6,1512) = 259.56$, $p < .05$, as well as a significant Age × Comparison Duration interaction, $F(12,1512) = 16.33$, $p < .05$. In line with previous studies of temporal generalization,

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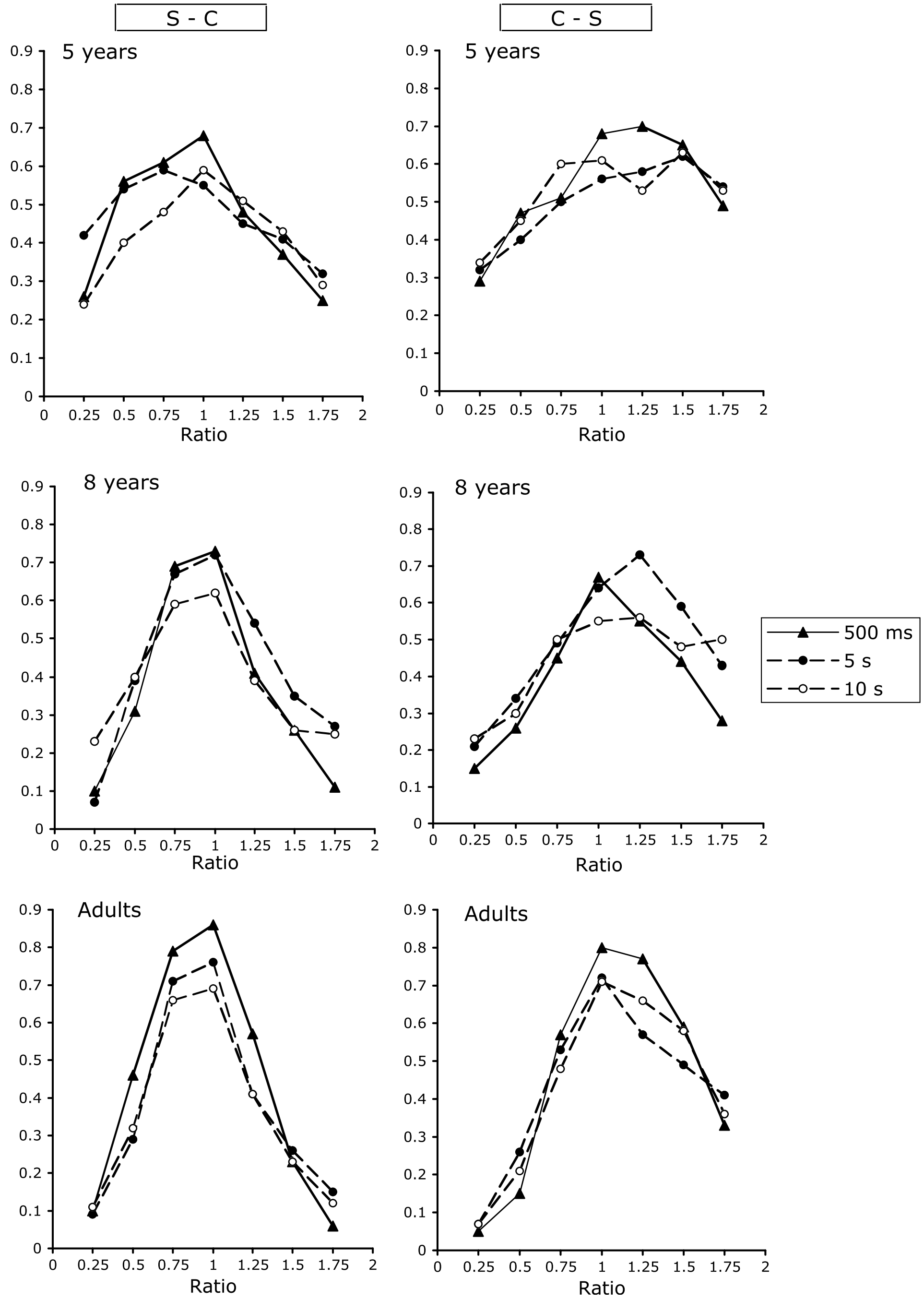

Fig. 1. Proportions of same responses plotted against the ratios to the standard duration (i.e., comparison stimulus duration) as a function of the retention interval between the two successive durations (500 ms, 5 s, or 10 s) for the three age groups and when the first duration (*s–c*, left panels) or the second duration (*c–s*, right panels) was the standard.

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this significant interaction indicated that the steepness of the generalization gradient increased with age, with sensitivity to time being lower in the younger children.

The overall ANOVA also revealed a significant Comparison Duration × Retention Delay interaction, $F(12,1512) = 4.06$, $p = .0001$, and a significant Comparison Duration × Retention Delay × Age interaction, $F(24,1512) = 1.74$, $p = .03$, although the main effect of retention delay was not significant, $F(2,252) = 0.601$, $p = .55$. There was no Retention Delay × Stimulus Duration Order interaction. No other interaction involving the delay was significant.

Fig. 2 illustrates the significant three-way interaction. To examine this three-way interaction, we conducted a two-way ANOVA for each age group on the proportion of same responses with the delay and the comparison duration as factors. In all age groups, there was a significant effect of comparison duration (5-year-olds: $F(6,522) = 29.80$; 8-year-olds: $F(6,252) = 76.45$; adults: $F(6,522) = 118.28$), all ps $< .05$, and no main effect of the delay (5-year-olds: $F(2,87) = 0.21$; 8-year-olds: $F(2,87) = 2.73$; adults: $F(2,87) = 1.83$), all ps $> .05$. The Comparison Duration × Retention Delay effect did not reach significance in the adults, $F(6,522) = 1.49$, $p > .05$. Whatever the retention delay, the generalization gradients in the adults were symmetrical, as indicated by the similar mean proportion of same responses between the short comparison durations (overall averaged for the 0.25, 0.50, and 0.75 ratios) and the long comparison durations (overall averaged for the 1.25, 1.50, and 1.75 ratios) (500 ms: $t(29) = 1.33$; 5 s: $t(29) = 0.99$; 10 s: $t(29) = 1.85$), all ps $> .05$, as well as between the 0.75 and 1.25 ratios (500 ms: $t(29) = 0.22$; 5 s: $t(29) = 1.80$; 10 s: $t(29) = 0.61$), all ps $> .05$. However, a post doc analysis revealed that the proportion of same responses for the standard duration (1.00 ratio) was lower for the 5-s and 10-s delays than for the 500-ms delay (5 s: $t(58) = 2.89$; 10 s: $t(58) = 3.58$), all ps $< .05$, whereas no difference was obtained between the 5-s and 10-s delays, $t(58) = 1.06$, $p > .05$. Thus, in the adults, a retention delay flattened the generalization gradient by reducing the proportion of same responses for the standard duration.

Unlike in the adults, the Retention Delay × Comparison Duration interaction was significant in the 8-year-olds, $F(12,522) = 3.10$, $p < .05$, and tended toward significance in the 5-year-olds, $F(12,522) = 1.77$, $p = .06$, indicating that the retention delay effect was relatively greater in the children than in the adults. The statistical analysis revealed that in children, as in adults, increasing the retention delay did not produce and increase a shortening effect in the generalization task. Indeed, whatever the retention delay, in the 5-year-olds and 8-year-olds, the generalization gradients were symmetrical, as shown by the similar mean proportion of same responses between the short and long comparison durations, as well as between the 0.75 and 1.25 ratios (all ps $> .05$), except for the 8-year-olds in the 5-s delay condition, where the proportion of same responses was greater for the long comparison durations than for the short comparison durations, .49 versus .36, $t(29) = -2.99$, $p < .05$, indicating a right asymmetrical gradient, opposite to a possible shortening effect. In contrast, increasing the retention delay flattened the generalization gradients in children, and particularly so in the 5-year-olds. The proportion of same responses for the standard duration was lower for the 5-s and 10-s retention delays than for the 500-ms retention delay in the 5-year-olds (5 s: $t(58) = 2.74$; 10 s: $t(58) = 1.98$), all ps $< .05$; in the 8-year-olds, it was lower for the 10-s retention delay, $t(58) = 2.49$, $p < .05$, but not for the 5-s retention delay, $t(58) = 0.52$, $p > .05$. Furthermore, although the generalization gradients flattened between 500 ms and 5 or 10 s, it did not become flatter as a function of the retention interval value in the 5-year-olds, with the proportion of same responses for the standard duration being similar to that for the 5-s and 10-s retention delays, $t(58) = 0.90$, $p > .05$. Nevertheless, there was a tendency for it to be higher for the 10-s delay than for the 5-s delay in the 8-years-olds, $t(58) = 1.96$, $p = .06$.

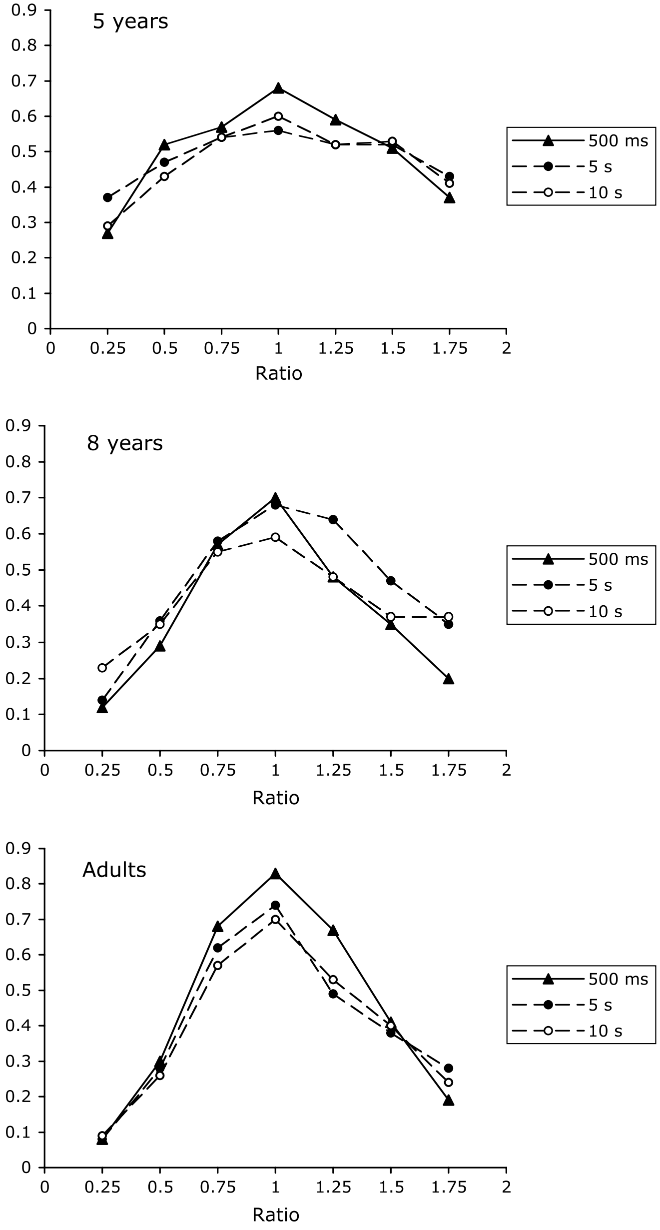

Fig. 2. Proportions of same responses plotted against the ratios to the standard duration (i.e., comparison stimulus duration) as a function of the retention interval between the two successive durations (500 ms, 5 s, or 10 s) for the three age groups (data combined across *s–c* and *c–s*).

In addition, as Fig. 2 suggests, with the retention delay, the 5-year-olds had difficulties in discriminating the different comparison durations, such that the delay-related flattening of the generalization gradient seemed to be relatively greater in the 5-year-olds than in the 8-year-olds and the adults, especially in the 5-s condition. Indeed, when we excluded the

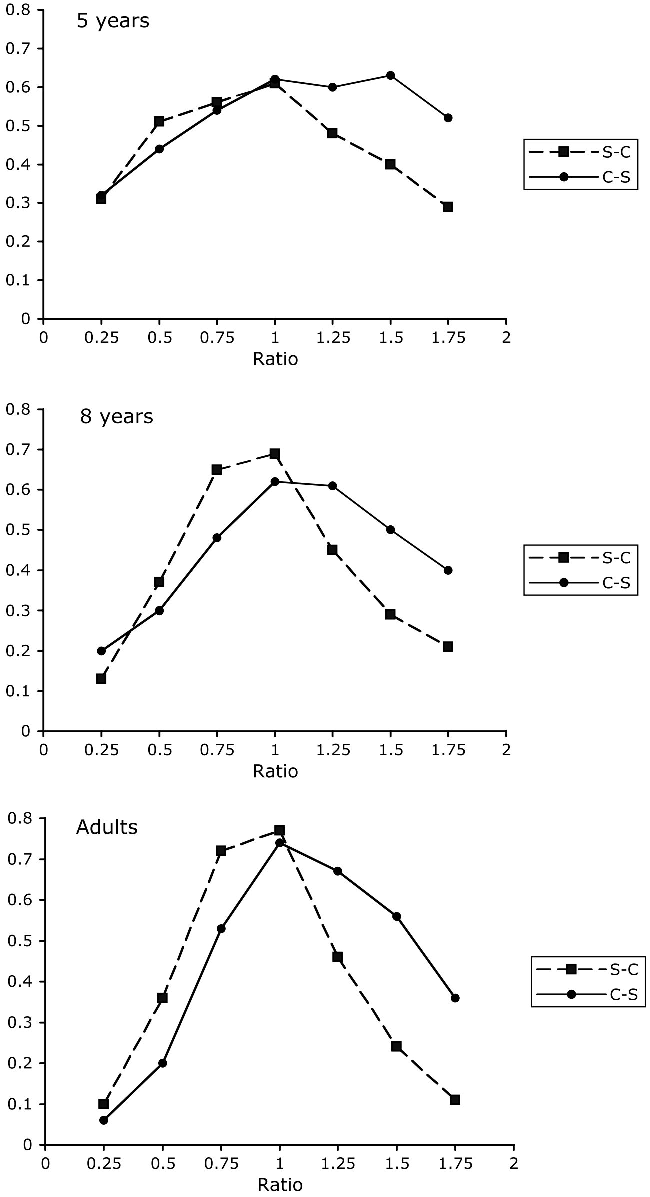

Fig. 3. Proportions of same responses plotted against the ratios to the standard duration (i.e., comparison stimulus duration) when the standard duration was presented first (*s–c*) or second (*c–s*) for the three age groups (data combined across retention interval).

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two anchor durations, the effect of comparison duration was significant for the 500-ms delay in the 5-year-olds, $F(4,116) = 5.02$, $p = .001$, but no longer was significant for the 5-s duration, $F(4,116) = 1.36$, $p < .05$. For the 10-s delay, a significant effect of the comparison durations occurred, $F(4,116) = 4.67$, $p < .05$. However, there was no effect of comparison duration when the 0.75, 1.00, and 1.25 durations were considered, $F(2,58) = 2.16$, $p < .05$, whereas this effect was observed in the 0-s delay, $F(2,58) = 4.64$, $p < .05$. Unlike in the 5-year-olds, the comparison effect continued to be significant despite the flattening of the generalization gradient with a retention interval in both the 8-year-olds (500-ms delay, $F(4,116) = 20.75$, 5-s delay, $F(4,116) = 11.57$, 10-s delay, $F(4,116) = 11.80$) and the adults (500-ms delay, $F(4,116) = 30.82$, 5-s delay, $F(4,116) = 19.44$, 10-s delay, $F(4,116) = 20.12$), all $ps < .001$.

The overall ANOVA also found a significant main effect of stimulus order (*s–c*/*c–s*), $F(1,252) = 12.92$, $p < .05$. Furthermore, the Stimulus Duration Order × Comparison Duration interaction, $F(6,1512) = 54.77$, $p < .05$, and the Stimulus Duration Order × Comparison Duration × Age interaction, $F(12,1512) = 2.42$, $p < .05$, were significant. Stimulus duration order did not interact with any other factor. Fig. 3 illustrates the significant three-way interaction by plotting the proportion of same responses against the ratios (i.e., comparison durations) in the *s–c* and *c–s* order condition for the 5-year-olds, the 8-year-olds, and the adults. For each age group, the figure reveals a systematic asymmetry in the generalization gradient. When the standard duration was presented first (*s–c*), the generalization gradient was shifted toward the left; when it was presented second (*c–s*), this gradient was shifted toward the right. The leftward shift of the generalization gradient indicated that the participants judged the short comparison durations to be identical to the standard durations more often than the long ones. Conversely, the rightward shift indicated that they produced more same responses for the long comparison durations than for the short ones. In each respective condition (*s–c*/*c–s*), the leftward and rightward shifts of the generalization gradient indicated that the first duration was judged to be shorter than the second one. In the *s–c*, because the first duration was the standard, a greater proportion of same responses was given for the short comparison durations. In the *c–s*, because the standard was presented second, the standard was judged to be longer given that the comparison duration presented first was judged to be shorter. Thus, Fig. 3 suggests that, in the comparison of two successive durations, the first was systematically judged to be shorter than the second, thereby reflecting a negative time–order error. However, the *c–s* gradient was not a perfect mirror image of the *s–c* gradient, presumably because of the different duration ranges used, with the standard never being longer than 2 s while the comparison could be up to 3.5 s. The subsequent analysis of each order of presentation condition taken separately confirmed this negative time–order error effect in each age group.

In the *s–c* condition, the mean proportion of same responses for the three comparison durations shorter than the standard (0.25, 0.50, and 0.75 ratios overall averaged) was higher than that for the three comparison durations longer than the standard (1.25, 1.50, and 1.75 ratios overall averaged) for the 5-year-olds, $t(44) = 2.10$, $p < .05$; the 8-year-olds, $t(44) = 2.34$, $p < .05$; and the adults, $t(44) = 4.25$, $p < .05$. In each age group, the participants confused the standard with the slightly shorter comparison duration (0.75 ratio) (5-year-olds: $t(44) = 1.59$; 8-year-olds: $t(44) = 1.00$; adults: $t(44) = 1.73$), all $ps > .05$, but not with the slightly longer comparison duration (1.25 ratio) (5-year-olds: $t(44) = 5.05$; 8-year-olds: $t(44) = 7.62$; adults: $t(44) = 11.53$), all $ps < .05$. Conversely, in the *c–s* condition, the participants in all of the age groups produced significantly more same responses for the longer comparison durations (overall average for 1.25, 1.50, and 1.75) than for the shorter comparison durations (overall average for 0.24, 0.50, and 0.75) (5-year-olds: $t(44) = 7.35$; 8-year-olds: $t(44) = 8.17$; adults: $t(44) = 7.78$), all $ps < .05$. These results indicated that the 5- and 8-year-olds confused the standard with the slightly longer duration (1.25) (5-year-olds: $t(44) = 0.66$; 8-year-olds: $t(44) = 0.28$), $ps > .05$, but not with the slightly shorter comparison duration (0.75) (5-year-olds: $t(44) = 2.82$; 8-year-olds: $t(44) = 4.85$), $ps < .05$. In the *c–s* condition, although the magnitude of the difference in the number of same responses was also smaller between the 1.00 and 1.25 ratios than between the 0.75 and 1.00 ratios, the adults succeeded in discriminating between the standard and the two close comparison durations, that is, the 1.25 ratio, $t(44) = 2.30$, $p < .05$, and the 0.75 ratio, $t(44) = 7.15$, $p < .05$.

Overall, these results confirm that a negative time–order error effect occurred in our comparative task whatever the age groups tested and the value of the interval retention used. However, this shortening resulting from the time–order error effect tended to be greater in the younger children. Unlike their older counterparts, in the *s–c* condition the 5-year-olds produced a similar proportion of same responses not only for the standard and 0.75 ratios, as mentioned above, but also for the 0.75 and 0.50 ratios, $t(44) = 1.86$, $p > .05$. Similarly, in the *c–s* condition, they produced similar proportions of same responses for the standard and 1.25 ratios as well as for the 1.25 and 1.50 ratios, $t(44) = 0.81$, $p > .05$. In this last condition, the generalization gradient appeared to be particularly flat for the comparison durations longer than the standard. Thus, the long durations were remembered less accurately than the short durations, especially by the 5-year-olds.

Modeling

To confirm the temporal processes suggested by the statistical analyses of the generalization performance, we modeled our data by using a variant of a "core" model of episodic temporal generalization, Eq. (1) below, developed by Wearden (2004). There are two stimuli present on each trial, s (standard) and c (comparison) in the current case, and the core model predicts that a same response occurs when

$$\mathrm{abs}(s^* - c^*)/\mathrm{mean}(s^*, c^*) < b^*. \tag{1}$$

Here s^* and c^* are transformed values of the real-time values of s and c. The transformation was accomplished by constructing a Gaussian distribution with an accurate mean (s or c) and some coefficient of variation, v, which is one of the parameters of the model. Values randomly sampled on each trial from these distributions are s^* and c^*. Also, mean(s^*, c^*) is the mean of s^* and c^* ($[s^* + c^*]/2$), abs indicates absolute value, and b^* is a threshold value. The mean threshold value is b, and this is transformed into a Gaussian distribution with mean b and coefficient of variation of 0.5, with b^* being a value randomly sampled from this distribution on each trial. Also, b is the second parameter of the core model. In principle the coefficient of variation of the b distribution could also be a parameter of the model (Wearden, 1992), but in practice the value always is close to 0.5, so this constant value has been used in most simulations since 1992.

When the ratio of s and c is varied, the model produces temporal generalization gradients that (a) are peaked at a ratio of 1.0 (when $s = c$) and (b) are slightly rightward skewed,

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so that when c is a ratio higher than 1.0 of s it tends to be more confused with it than when the ratio is less than 1.0. The reason for this is the use of the mean of s and c in the denominator of Eq. (1), meaning that a given abs($s^* - c^*$) difference will be less likely to produce a same response when c is smaller (i.e., smaller value of c/s).

The two parameters of the core model reflect different psychological processes. The parameter v can be thought of as reflecting the variability or "fuzziness" of the time representations of s and c. Larger v values make the representation of s and c more variable from one trial to another even if their real-time values are constant. The parameter b reflects the decision process, where smaller b values indicate a more conservative decision for making a same response. Changing the values of the two parameters produces different effects on the output of the model; increasing v makes the predicted gradients flatter (i.e., the different c/s ratios are discriminated more poorly), and changing b affects the overall levels of "yes" responses, with more yes responses occurring with higher b values.

To model developmental and other trends in the current work, the core model was modified in two ways. The first was the addition of a "random responding" or "inattention" parameter, p. As mentioned above, increases in v will flatten temporal generalization gradients, but a problem with data from young children is that they exhibit clear sensitivity to the time values presented while at the same time showing high rates of response at the most "distant" times (the 0.25 and 1.75 ratios in this case). Increasing v to levels needed to simulate the proportion of yes responses found at these distant times removes all sensitivity to the c/s ratio, so something else is required, and here we follow Droit-Volet and colleagues (2001) in introducing another parameter that reflects the probability, on each trial, of responding same or different at random (i.e., with a 50% probability of each) without regard to the stimulus durations presented. So, on some proportion p of trials, same/different responses occur at random, whereas on proportion $1 - p$ of trials, the core model (with a modification discussed below) generates the response. Droit-Volet and colleagues used a similar parameter in their modeling of "normal" temporal generalization in children and found that the value of this parameter declined with increasing age, presumably reflecting increasing task attention in older children and adults in the generalization task.

The second modification was needed to accommodate the time–order error effects noted in the current data, that is, the fact that gradients were different on s–c and c–s trials. The core model makes no distinction between the two stimuli s and c, but a time–order error can be incorporated by multiplying the s or c value (whichever came first on the trial) by a value m. If m is less than 1.0 (as it is in all of the simulations we report), the second stimulus is biased toward being judged as longer than the first, producing a negative time–order error.

The data were modeled using the two modifications of Eq. (1), so four parameters were derived: v (the "fuzziness" of time representations), b (the threshold), p (the probability of random responding), and m (the time–order error multiplier). Inspection of the generalization gradients obtained from participants of all ages suggested that they flattened as the delay between the stimuli increased. One potential source of such flattening is an increase in v with increasing delay, but this effect, if present, would affect only the first stimulus presented and not the second because the second stimulus is processed shortly after being presented. The model was first fitted to data from the 500-ms interstimulus interval, with the same v value being used for both the first and second stimuli presented. To model the effects of the 5- and 10-s delays, we kept the v for the second stimulus at the value obtained from the fit of the 500-ms condition and explored the possibility that the v value for the first stimulus had changed (i.e., the "noise" in the representation of the first stimulus had increased with increasing delay). The v values shown in Table 1 at the 5-s and 10-s delays are the values for the first stimulus.

The model was embodied in a Visual Basic 6.0 (Microsoft) program, which produced the average 10,000 trials at each duration ratio used, and the parameter values were varied over a wide range until the smallest mean absolute deviation (*MAD*) between the model's predictions and obtained data was obtained. The *MAD* was calculated as the sum of the absolute differences between the output of the model and data divided by 7 (the number of data points simulated). Table 1 shows the values of each parameter obtained in this manner for the three age groups. The model fitted the data reasonably well, although the fit was better for the *s–c* conditions than for the *c–s* ones.

The general developmental trends obtained involved changes in only two of the modeling parameters: v and p. The others parameters, b and m, did not change markedly or systematically with age. The v values generally decreased with increasing age, being larger

Table 1
Fitted model parameter values for the episodic generalization task with two stimulus durations presented on each trial separated by a retention interval (500 ms, 5 s, or 10 s) when the first duration was the standard duration (*s–c*) or the comparison duration (*c–s*)

	v	b	p	m	*MAD*
s–c					
5-year-olds					
500 ms	0.21	0.48	0.45	0.76	0.03
5 s	0.55	0.52	0.60	0.70	0.03
10 s	0.60	0.48	0.35	0.86	0.03
8-year-olds					
500 ms	0.15	0.35	0.20	0.85	0.03
5 s	0.25	0.42	0.20	0.90	0.03
10 s	0.35	0.42	0.35	0.80	0.03
Adults					
500 ms	0.10	0.38	0.07	0.88	0.03[a]
5 s	0.22	0.38	0.12	0.85	0.03
10 s	0.27	0.37	0.05	0.85	0.02
c–s					
5-year-olds					
500 ms	0.20	0.52	0.45	0.88	0.05
5 s	0.38	0.54	0.45	0.85	0.04
10 s	0.50	0.65	0.45	0.92	0.04
8-year-olds					
500 ms	0.26	0.34	0.12	0.94	0.04
5 s	0.48	0.60	0.20	0.84	0.05
10 s	0.55	0.50	0.22	0.90	0.04
Adults					
500 ms	0.14	0.38	0.05	0.93	0.03
5 s	0.32	0.4	0.10	0.96	0.04
10 s	0.38	0.42	0.08	0.98	0.04

Note. Parameters: v, coefficient of variation of the stimulus durations; b, decision threshold; p, probability of random responding; m, multiplier for time–order error, with $m < 1.00$ indicating a shortening of the first duration; *MAD*, mean absolute deviation.

[a] 1 point excluded from *MAD* calculation.

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in the 5-year-olds than in the 8-year-olds and larger in the 8-year-olds than in the adults. However, the *v* values were close in the two groups of children in the *c–s* conditions when a retention delay was introduced between the two stimulus durations to be compared. Therefore, our findings are consistent with the idea that the representation of time on each trial is more variable in the younger children (e.g., Delgado & Droit-Volet, 2007; Droit-Volet, 2003; Droit-Volet & Clément, 2005; McCormack et al., 1999). In addition, the probability of random responding, expressed in the *p* parameter, was particularly high in the 5-year-olds, explaining their worse performance in the temporal generalization task with a forced choice without feedback (Droit-Volet & Izaute, 2005), and *p* declined systematically with increasing age in all conditions.

So far as the effect of retention delay was concerned, the only parameter that changed systematically and consistently with the increase in the retention delay was the *v* value. The *m* parameter value, which would have reflected any potential shortening of the perceived duration of the first stimulus with increasing delay, did not change consistently with retention delay. Thus, in accordance with our previous statistical analyses, increasing the retention delay increased the *v* parameter value, thereby making the representation of time fuzzier, and that in turn was the principal mechanism responsible for the flattening of the generalization gradient. Inspection of the modeling of our data also suggests that the magnitude of the increase of the *v* parameter value was larger between the 500-ms and 5-s retention delays than between the 5-s and 10-s delays. The total amount of noise introduced in time representation by the increase in retention delay between 500 ms and 5 s, reflected in the change in *v*, was largest in the 5-year-olds in the *s–c* condition, but values were close in the three age groups in the *c–s* conditions (.18, .22, and .18 for the three groups in order of increasing age). The further increase in retention delay between 5 s and 10 s produced similar increases in *v* for all groups (.05–.12).

Finally, in both the *s–c* and *c–s* conditions, the *m* parameter values were less than 1.0, indicating a shortening effect of the first stimulus duration. This confirms the negative time–order error underlying the leftward-skewed gradient in the *s–c* and the rightward-skewed gradient in the *c–s* condition. The other parameters were not affected by the stimulus order. Inspection of the *m* values produced again showed overlap in values across the different age groups, particularly in the *c–s* condition, but there was a slight suggestion in the *s–c* condition that the time–order error was more marked in the youngest children at the shorter two interstimulus delays. However, overall, evidence for developmental trends in time–order error magnitude was weak. In sum, parameter values from our model were in good accord with the results of the statistical analyses of generalization performance by showing that increasing the retention interval increased the variability in the temporal representation but did not produce an increasing shortening effect for the first presented duration as the retention interval increased. According to our results, any shortening effect present was a negative time–order error independent of retention interval.

Discussion

This experiment investigated the retention of duration in short-term memory in 5- and 8-year-olds as well as in adults. The results showed that, in a task requiring a comparison of two successive stimulus durations, a negative time–order error occurred in all age groups. Furthermore, our results showed that increasing the retention delay between two durations did not produce a choose short effect but decreased accuracy of time judgments by flattening the generalization gradients, and this occurred to a greater extent in the children than in the adults. However, increasing the retention delay up to 10 s did not amplify this flattening effect. Our model suggests that the flattening of the generalization gradient with the retention delay was due to an increase in the v parameter, that is, an increase in the variability of time representation. In addition, the increase in the v parameter between the 500-ms and 10-s retention intervals appeared to be the smallest in the adults in both the *s–c* and *c–s* conditions. This suggested a developmental difference in the retention delay effect on the variability in time representation. However, this developmental trend in the v parameter was not always consistent, with the children sometimes showing changes equivalent to those of adults.

On the basis of the choose short effect obtained in animals, Spetch and Wilkie (1983) stated that the decay of the representation of duration over time produces a subjective shortening effect. Wearden and Ferrara (1993) and Wearden and colleagues (2002) also found evidence for subjective shortening in humans. Data in the current study showed no evidence of subjective shortening, showing instead that increasing the length of retention of a duration in short-term memory increased the variability of time representations rather than shortened them.

Why are the current results different from those of Wearden and Ferrara (1993)? One possibility is that the differences are due to differences in the responses permitted. In their Experiments 2 and 3, Wearden and Ferrara required participants to judge whether the second stimulus was longer than, shorter than, or equal in duration to the first stimulus, unlike in the current work, where the responses were "equal or not," as in the temporal generalization task. However, in their Experiment 1, Wearden and Ferrara just asked participants whether or not the duration of the two stimuli was the same, and they observed a progressive increase in "no" responses as the *s–c* interval increased (see, e.g., their Fig. 1 [Wearden & Ferrara, 1993, p. 169]). This was interpreted as resulting from subjective shortening of *s*, but in fact it may be just as consistent with a change in variability of time representations with increasing *s–c* interval, as if the memory of *s* becomes more variable as the retention interval increases, and this may lead to an increasing tendency to conclude that the *s* and *c* durations are not the same. Thus, data from Wearden and Ferrara's Experiment 1, which used the same response alternatives as the current study, might not actually be incompatible with the results reported here.

We should also note that in addition to the stimuli used in Wearden and Ferrara's (1993) experiments being shorter on average (400 ms) than those used here, the difference between *s* and *c* was generally less marked in their experiments than in the current study. For example, when *s* and *c* were different in Wearden and Ferrara's experiments, there was at most a 100-ms difference, which is on average 25% of *s*. This was the smallest percentage difference used in the current study, so yet another possibility is that the subjective shortening effects are manifested only when *s* and *c* are similar. Such a possibility is not implausible, particularly when coupled with a yes/no decision like the one used in the current work. For example, if *s* and *c* are very different, subjective shortening of *s* might have no effect on the ability to decide that *s* and *c* are not the same. However, the current study did include some "difficult" cases (e.g., the 0.75 and 1.25 multiples), where subjective shortening might be expected to manifest itself, if present, as it also would in the 1.00 multiple, where *s* and *c* have the same duration. In general, then, it remains unclear why subjective shortening apparently is clearly manifested in some cases (Wearden & Ferrara,

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1993; Wearden, Goodson, & Foran, in press; Wearden, Parry, & Stamp, 2002) but not in others.

Although work during the 1980s by Spetch and colleagues (e.g., Spetch & Wilkie, 1983) found evidence for subjective shortening, some more recent studies with animals have failed to find it in all cases or with all types of stimuli (Dorrance, Kaiser, & Zentall, 2000; Grant & Spetch, 1993; Santi et al., 1995; Spetch & Rusak, 1989), suggesting that the presence or absence of subjective shortening may be affected critically by procedural factors that are not yet completely understood (for a recent review, see Wearden et al., in press). In contrast, a shortening effect on time judgments has nearly always been found in studies investigating interference from nontemporal tasks on the processing of duration (e.g., Brown, 1997; Fortin & Massé, 1999; Fortin & Rousseau, 1998; Neath & Fortin, 2005). In these studies, the nontemporal inference occurred during the encoding of time by the accumulation process, which is under the control of working memory. Thus, this shortening effect probably is due to an interruption in the accumulation process that provides the raw material for the representation of time. Consequently, the processing of durations under the control of working memory needs to be dissociated from the maintenance of durations in short-term memory (Fortin, 1999). Because our study dealt with the short-term retention of durations, it would seem to indicate that, in the comparative judgment of two signal durations, the retention of the first presented duration over a period of time does not produce a shortening effect but does increase the number of errors made when judging the equality of two durations, and our modeling suggested that this was due to the increase with retention delay in the amount of noise in the representation of the duration retained.

In addition, and especially in the *s–c* condition according to our model, our study revealed that the number of time judgment errors related to the retention delay was greater in the 5-year-olds than in the 8-year-olds and adults, with the two latter age groups obtaining closer values. On the basis of our model, we may assume that this was due to greater forgetting of durations when these were kept in short-term memory. Furthermore, in the youngest children, the v value was particularly high in the 500-ms condition prior to the introduction of a retention interval. Thus, we can assume that the forgetting in short-term memory might be also be related, at least in part, to the initial encoding of signal durations that was noisier in the younger children. Indeed, further increasing the noise level in the representation of the first signal duration would considerably reduce the possibility of children producing correct similarity judgments.

However, several developmental studies have indicated that children's general cognitive capacities are limited in specific terms of short-term memory (Cowan et al., 2003; Gathercole, 1998; Gathercole et al., 2004; Pickering, 2001; Towse & Cowan, 2005). The sources of these age-related changes in short-term memory have still not been clearly identified. Furthermore, related attentional processes interfere with the abilities to keep information in memory. Studies using attentional distractors have shown how age-related improvement in abilities to resist interference affects time perception (Droit-Volet et al., 2006; Gauthier & Droit-Volet, 2002). Similarly, children with attention deficit/hyperactivity disorder (ADHD) show particular impairment in time reproduction related to their poor behavior inhibition (Barkley, Koplowitz, Anderson, & McMurray, 1997; Meaux & Chelonis, 2005; Smith, Taylor, Rogers, Newman, & Rubia, 2002). However, as specifically concerned with the short-term retention, two main sources have been suggested: changes in the rehearsal strategy and increases in processing speed. Some studies have revealed that, up to the age

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of 7 years, children are unable to spontaneously use (i.e., without instructions from an adult) a mental rehearsal strategy that refreshes the memory trace in short-term memory to prevent decay (Gathercole & Hitch, 1993). Other studies have shown that the processing speed—which is related to neurological maturation—is slower in 5-year-olds and that the increase in processing speed contributes to an increase in short-term memory capacity in children (Gathercole & Hitch, 1993; Kail, 1986).

Whatever the mechanisms involved in the age-related changes in the retention of duration in short-term memory, our study also showed that the processing of two successive durations produced an underestimation of the first duration relative to the second one, as indicated by the negative time–order error effect obtained. Several theoretical attempts have been made to explain the time–order error effect (Hellström, 1985). One of these is the decay of the memory trace for duration. However, negative time–order error effects have been obtained with very short interstimulus intervals (i.e., 500 ms) for which no degradation of information occurs in working memory. Another explanation points to retroactive interference from the second signal duration on the first one while the latter is being processed by the working memory buffer. This retroactive hypothesis is consistent with the results found by Jamieson and Petrusic (1975), where the negative time–order error effect became less pronounced as the delay between the two signal durations increased. However, in our study, the time–order error effect appeared to be the same whatever the retention interval value used. Probably because it relates to working memory processes, our study suggests that the negative time–order error effect tended to be greater in the younger children. In line with these results, studies of the effect of interference from nontemporal information on time estimation have shown that attention interference produces a greater shortening effect in younger children due to their limited attentional capacities (Arlin, 1986; Gauthier & Droit-Volet, 2002; Zakay, 1992).

In conclusion, the current study has shown that in judgments of the similarity of two successive durations separated by a retention interval, the retention of the first duration in short-term memory reduces temporal accuracy.

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