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The effects of interference and retention delay on temporal generalization performance

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This study investigated the effect of forgetting of the standard duration on temporal discrimination in a generalization task. In two experiments, participants were given a temporal generalization task with or without a retention delay between the learning of the standard duration and the testing of the comparison durations. During this delay, they either performed or did not perform an interference task. Results failed to reveal any effect of 15-min and 24-h retention delays on time judgments (Experiment 1). However, when an interference task was performed during the 15-min delay (Experiment 2), there was a subjective shortening effect, indicating that the standard duration was judged shorter with than without an interference task. These findings suggest that when an interference task occurs immediately after initial temporal encoding, it affects the process of consolidation in reference memory.

Estimating the duration of an event often requires reference to memory for the durations of similar past events. The ability to maintain these durations in long-term memory is therefore crucial for time estimation. Even so, we know relatively little about the maintenance of temporal long-term memories. To quote Ogden, Wearden, and Jones (2008), "the answers to many fundamental questions about properties of reference memory for duration remain uncertain" (p. 1525). This gap in our knowledge is all the more surprising given the importance of memory processes in the most influential theory of timing, scalar expectancy theory (SET; Gibbon, 1977; Gibbon, Church, & Meck, 1984). This theory assumes that time estimation involves three successive processing stages: encoding, maintenance of the event duration in memory, and decisional processes. At the encoding level, a pacemaker-counter mechanism, or internal clock, provides the raw representation of duration. This representation is then stored in short-term working memory and can be transferred to long-term reference memory, which contains representations of important durations, such as standard durations. Time judgments are therefore based on a comparison of the representation of the present duration with those of other durations maintained in reference memory. According to this theory, one important source of variance in time judgments would be the representation of durations in reference memory. The aim of the present study was to examine whether the long retention delays degrade traces in temporal reference memory, thereby disrupting time judgments.

Few studies have examined the properties of temporal reference memory in human adults (Delgado & Droit-Volet, 2007; Grondin, 2005; Jones & Wearden, 2003, 2004; Ogden & Jones, 2009; Ogden, Wearden, & Jones, 2008, 2010; Penney, Gibbon, & Meck, 2000; Rattat & Droit-Volet, 2005), and most of these have focused on manipulating the temporal encoding and storage processes. Jones and Wearden (2003), for instance, increased the number of presentations of an auditory standard duration (from one to five), assuming that this would reduce reference memory variability in a generalization task. However, what they actually found was that the number of standard presentations had no effect on time judgments. Only in a visual reproduction task did multiple presentations of the standard duration increase temporal accuracy (Ogden & Jones, 2009), and this benefit was lost when an attentional cue was provided prior to the first standard duration presentation, suggesting a problem in the encoding of the visual standard duration rather than a problem with reference memory per se. Other researchers have increased the load in reference memory by asking participants to encode either different standard durations (Jones & Wearden, 2004) or the same standard duration that was presented in different sensory modalities—auditory and visual (Penney et al., 2000)—or even different standard durations that were presented in different sensory modalities (Grondin, 2005). Results indicate that increasing the load in memory increases discrimination errors when different standard durations are presented in the

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same modality but not when they are presented in different modalities. Whatever the case, it is noteworthy that all these studies focused on the encoding of standard durations in memory and its consequences on time discrimination, rather than on the effect of the long-term retention of standard durations, once they have been learned and stored in reference memory.

Using a modified temporal generalization task, Ogden et al. (2008) recently tested the effect of a retention delay between the presentation of a standard duration and the testing of comparison durations (shorter than, longer than, or equal to the standard duration). The participants' task was to judge whether or not each comparison stimulus had the same duration as the standard duration. Results showed that a retention delay between the presentation of the standard duration and its subsequent testing had no significant effect on temporal generalization gradients. In contrast, the latter were clearly disrupted when the retention delay was filled with an interference task that was similar to the testing task but involved a different standard duration. More specifically, the gradients shifted toward the left when the second standard duration was longer than the first one and toward the right when it was shorter, as compared with the other conditions. The modeling of data using the modified Church and Gibbon's (1982) model (MCG model) developed by Wearden (1992) for human adults suggested that the interference task not only increased variability in the representation of the standard duration in reference memory, but also distorted this referent duration. Ogden et al. (2008) therefore concluded that interference was the main source of deterioration for temporal reference memory in a generalization task. In their study, however, the interference task was not a nontemporal task, but a temporal one. The memory representation of the standard duration may therefore have been a mix of the two standard durations, rather than reflecting impairment of the first standard duration by the second one (see also Penney et al., 2000). Moreover, since the retention delays used in this study were short (between 0 and 45 sec), the authors tested the effect of a retention delay on short-term temporal memory rather than on long-term temporal memory.

There are fundamental differences between short-term memory and long-term memory (for a recent review, see Cowan, 2008). According to Baddeley and Hitch's (1974) model, short-term memory refers to the temporary storage and rehearsal of information, whereas long-term memory is relatively permanent. For example, short-term memory allows you to retain a phone number before and while you are dialing that number. When information is stored in long-term memory, it undergoes a consolidation process that strengthens its memory trace (McGaugh, 2000). In the case of short retention delays, such as those used by Ogden et al. (2008), the interference task therefore affects the rehearsal process in short-term memory. In contrast, for longer retention delays ($\geq$15 min), an interference task that occurs just after the learning phase affects memory consolidation, rather than rehearsal. The consolidation process begins straight after learning and is intended to consolidate the information in long-term memory (for reviews, see Lechner, Squire, & Byrne, 1999; McGaugh, 2000). Although the time course of the consolidation has not yet been clearly delineated, this process must be relatively fast, taking a few hours at most (Dudai, 2004; Sara & Hars, 2006). Wixted's (2004, 2005) model of forgetting assumes that memories during this consolidation period are especially vulnerable to subsequent induction associated with the formation of new memories, whether or not these are similar to the ones they impair (Skaggs, 1925). Thus, performing an interference task during the consolidation process should degrade traces in long-term memory.

In the present article, we therefore ran two experiments to further examine the effect of long retention delays and interference on temporal generalization performance. The generalization task consisted of two phases: a learning phase of the standard duration and a testing phase of the comparison durations. In the first experiment, either a long retention delay, lasting either 15 min or 24 h, or no delay (i.e., immediate condition) was inserted between the learning and testing phases. We hypothesized that if the temporal reference memory were, indeed, affected by the maintenance of duration in memory per se, we would see a flattening of the temporal generalization gradient, reflecting reduced sensitivity to time. This flattening of the generalization gradient would be more pronounced not only when there was a retention delay, but also when that retention delay lasted for 24 h rather than 15 min. In the second experiment, we investigated the effect on temporal generalization gradients of a nontemporal interference task administered during a 15-min retention delay. Two ranges of durations were tested, one shorter than 1 sec and the other longer, in order to verify whether the possible effects of retention delay or inference depended on whether short or long durations were used.

EXPERIMENT 1

Method

Participants. Forty-five psychology students from Clermont-Ferrand, France (28 women, and 17 men; mean age, 25.01 years, *SD* = 0.57) participated in the present experiment on a voluntary basis.

Materials. The participants were tested individually in a quiet room in front of a PowerMacintosh computer about 50 cm from the screen. The computer controlled the experiment and recorded data via the PsyScope program (Cohen, MacWhinney, Flatt, & Provost, 1993). The visual stimuli were blue circles (4.5 cm in diameter) displayed in the center of the computer screen. Responses consisted of pressing the "S" or the "L" keys of the computer keyboard. Each response made during the learning phase was immediately followed by positive (smiling clown) or negative (frowning clown) feedback displayed in the center of the computer screen for 2 sec.

Design. A between-subjects design was used, in which participants were randomly assigned to one of the three experimental conditions (15 participants per group) according to the duration of the retention delay between the learning and testing phases: immediate, 15 min, and 24 h. In the immediate testing condition, the generalization test was performed immediately after the end of the learning phase. In contrast, in the other two conditions, the participants completed the generalization test 15 min and 24 h after the training, respectively. During the 15-min retention delay, the participants remained in the laboratory and waited. They could ask the experimenter, who was out in the corridor, only one or two questions. During the 24-h retention delay, the participants did not perform any specific task and simply engaged in their day-to-day activities.

Procedure. The experiment was conducted on an individual basis. Each participant was submitted to a generalization task consisting of two successive phases: learning and testing. In all three experimental conditions, the learning phase began with the presentation of the standard duration (4 sec), five times successively. The experimenter simply said "Look carefully, it's your circle. It stays on for a certain amount of time." Participants were then told to press one key if a comparison duration matched the standard duration and another one if it differed from it (i.e., either 0.5 or 7.5 sec). More specifically, they received the following instructions: "If you think the circle stayed on for the same time as your circle, press this key (*yes* responses), and if you think it stayed on for a shorter or longer time than your circle, press that key (*no* responses)." The buttonpress order was counterbalanced. Each participant completed at least two successive blocks of four trials, two for the standard duration and two for nonstandard durations. The intertrial interval value was randomly chosen between 1 and 2 sec. Correct responses resulted in positive feedback, and incorrect responses in negative feedback. Learning ended when the participant made no errors on consecutive eight trials. All participants needed only one block of eight trials to meet this criterion.

In the testing phase, participants performed seven blocks of nine trials, one for each nonstandard stimulus duration (1, 2, 3, 5, 6, and 7 sec) and three for the standard stimulus duration (4 sec). The different stimulus durations were presented in random order within each block of trials, and the intertrial interval was randomly chosen between 1 and 3 sec. The experimenter introduced the test by saying, "It's the same game, but now you won't receive any feedback." Moreover, the experimenter explicitly told all the participants not to count, adding that if they did count, the results would be distorted. An unpublished study that was recently conducted in our laboratories showed that this instruction is just as effective as other frequently used instructions, such as articulatory suppression, in preventing participants from using a counting strategy.

Results

Figure 1 illustrates the proportion of *yes* responses (i.e., identification of a stimulus as having the same duration as the standard one) plotted against comparison stimulus durations for the immediate and retention delay conditions. Initial inspection of the data suggested that the generalization gradients were skewed toward the right in all conditions and that increasing the retention delay had no effect on participants' temporal performance. This was confirmed by the statistical analyses.

An ANOVA[1] was run on the proportion of *yes* responses, with condition as a between-subjects factor and stimulus duration as a within-subjects factor. There was a significant effect of stimulus duration [$F(6,252) = 95.83$, $p < .0001$, $\eta_p^2 = .69$]. In contrast, neither the main effect of condition nor the stimulus duration × condition interaction was significant (both Fs < 1). Thus, the ANOVA on the proportion of *yes* responses indicated that the insertion of a retention delay between the learning and testing phases did not significantly degrade the participants' temporal generalization performance, whatever its duration (i.e., 15 min and 24 h).

Discussion

In Experiment 1, the similarity in generalization gradients for the three testing conditions suggested that participants did not forget the learned standard duration after a 24-h retention delay. As such, it not only confirmed Ogden et al.'s (2008) finding that imposing a retention delay of 0–45 sec between the presentation of the standard duration and the generalization test does not significantly

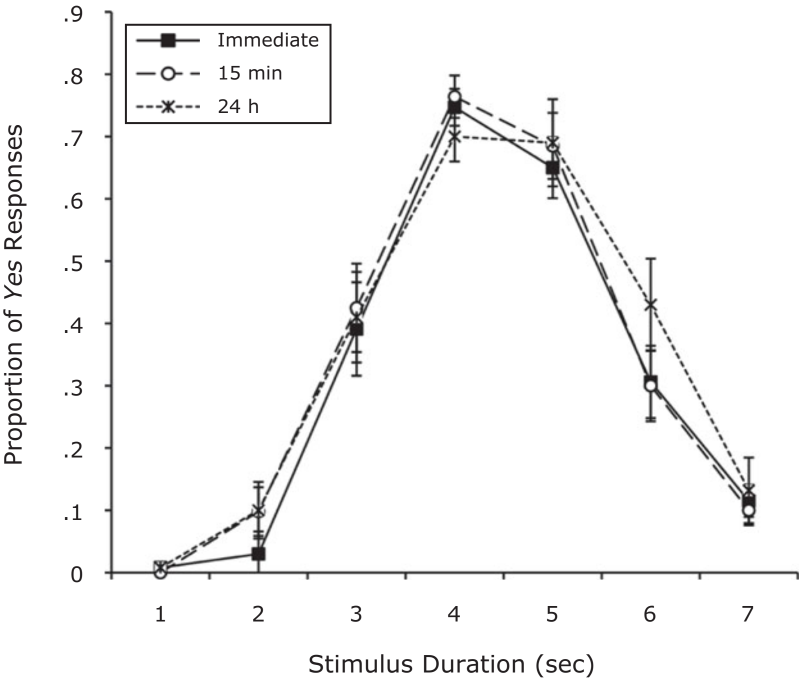


Figure 1. Proportions of *yes* responses (comparison duration = standard duration) plotted against comparison stimulus durations for the immediate, 15-min, and 24-h conditions in Experiment 1.

distort the generalization gradients, but also extended it to cover considerably longer delays. However, since previous studies of the memory consolidation process (Dudai, 2004; Wixted, 2004, 2005) have suggested that participants' time estimations are disrupted to a greater extent by a long retention delay if it is filled with an interference task, we tested this in the second experiment below. It is also important to specify that the interference task does not have to be temporal in nature for it to affect time judgments. Wixted (2004) stated that "even if the intervening study material is not related to the original learning in any obvious way, the new learning draws on a limited pool of resources that may otherwise be available to consolidate the original learning" (p. 247). In the spatial domain, for example, a recent study showed that the similarity between learned information and interference information is not an essential element for the emergence of forgetting (Tlauka, Donaldson, & Wilson, 2008, Experiment 2). In our experiment, we therefore chose a nontemporal interference task: a parlor game (see also Rattat & Droit-Volet, 2005). This game is particularly distracting for a long retention delay of 15 min. The interference task was administered in order to disrupt the process of consolidation in long-term memory of the learned standard duration.

A further purpose of Experiment 2 was to extend the investigation of the effects of retention delays with or without interference to durations shorter than those used in Experiment 1 (i.e., durations less than 1 sec). Shorter durations are often used with adults to prevent them from counting (e.g., Grondin, Meilleur-Wells, & Lachance, 1999; Grondin, Ouellet, & Roussel, 2004; McCormack, Wearden, Smith, & Brown, 2005; Wearden, 1992). However, some studies have suggested that the processing of long durations is actually different from that of shorter ones, because tracking the former demands more sustained attentional effort than tracking the latter (Grondin, 2001; Kagerer, Wittmann, Szelag, & Steinbüchel, 2002; Lewis & Miall, 2006; Rammsayer, 2006). The effect of interference on temporal generalization performance might therefore be specific to long durations and not to shorter ones. Accordingly, in the following experiment, we compared the effects of a 15-min interference task and a 15-min retention delay between the learning and testing phases on time judgments in a temporal generalization task, both with a long (i.e., 1- to 7-sec) and a short (i.e., 100- to 700-msec) duration range.

EXPERIMENT 2

Method

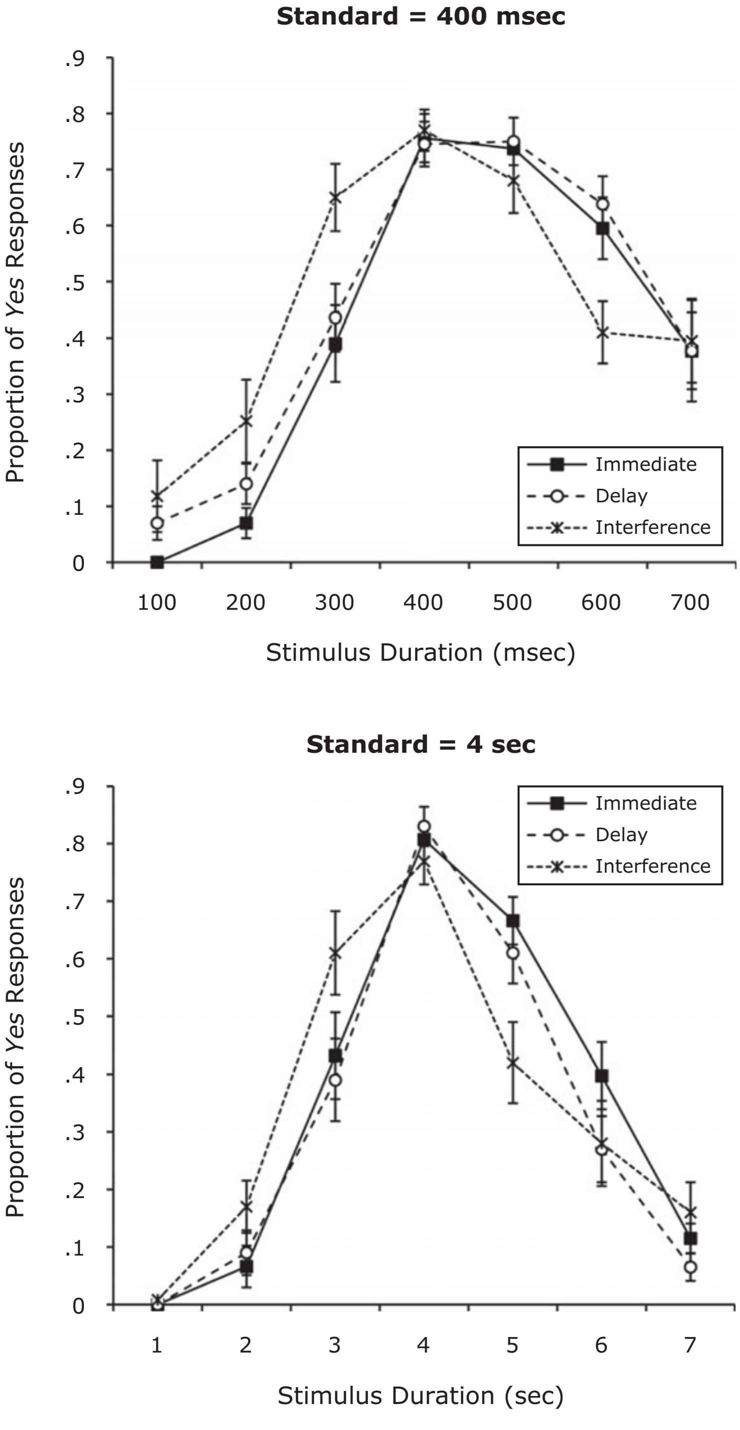
Participants and Design. The sample of this experiment consisted of 90 new voluntary psychology students from Clermont-Ferrand, France (71 women, 19 men; mean age, 22.02 years, *SD* = 0.36). A (3 × 2) between-subjects design (immediate, delay, or interference × 100–700 msec or 1–7 sec) was used. Participants were randomly divided into six experimental conditions (15 participants per group), according to the duration range (100–700 msec vs. 1–7 sec) and the testing condition (immediate vs. delay vs. interference).

Materials and Procedure. The materials and the procedure were the same as those used in Experiment 1 in the immediate and the 15-min delay conditions. However, we added a new test condition in which the 15-min retention delay was filled with a specific interference task—namely, the well-known game of "Snakes and Ladders," the principle of which is to roll a die and move along the squares. The winner is the person who reaches the 100th square first. If the player lands on the bottom of a ladder, he/she is carried to the top of that ladder, but if he/she lands on the head of a snake, he/she slides down to the bottom of that snake. We also added a shorter duration range condition, in which the standard duration was 400 msec and the nonstandard durations were 100, 200, 300, 500, 600, and 700 msec.

Results

An ANOVA[1] was performed on the proportion of *yes* responses, with condition and duration range as between-subjects factors and stimulus duration as the within-subjects factor. The ANOVA revealed significant main effects of stimulus duration [$F(6,504) = 170.97, p < .0001, \eta_p^2 = .67$] and duration range [$F(1,84) = 32.86, p < .0001, \eta_p^2 = .28$] and a significant interaction between the two [$F(6,504) = 7.87, p < .0001, \eta_p^2 = .09$]. The last result suggests that the accuracy of temporal discrimination was greater with the long duration range than with the short one. As can be clearly seen in Figure 2, the generalization gradients were steeper in the 1- to 7-sec range than in the 100- to 700-msec one. Moreover, although the main effect of condition was not significant ($F < 1$), the stimulus duration × condition interaction did reach statistical significance [$F(12,504) = 4.57, p < .0001, \eta_p^2 = .10$]. There was no other significant interaction with the condition and duration range factors [condition × duration range, $F(2,84) = 1.29, p = .28$; stimulus duration × condition × duration range, $F < 1$]. These results demonstrated that the effects of interference on generalization performance were relatively similar for both the long (4-sec) and the short (400-msec) durations.

The significant interaction between stimulus duration and condition suggests that the interference task affected the shape of the generalization gradients, regardless of the duration range. To examine this interaction more closely, we initially tested the effect of condition on the comparison durations that were identical to the standard durations, using a one-way ANOVA. There was no significant effect of condition ($F < 1$), indicating that the proportion of *yes* responses was no lower in the delay condition (with or without interference) than it was in the immediate condition. In contrast, there was greater confusion between the standard durations and shorter comparison durations in the interference condition than in the other two conditions. This suggested a shortening effect, with more short durations being judged as identical to the standard one. We therefore compared the proportions of *yes* responses for the comparison stimuli that were shorter than the standard durations (i.e., the mean proportion of *yes* responses for Stimuli 1, 2, and 3) with those that were longer (i.e., the mean proportion of *yes* responses for Stimuli 5, 6, and 7). Consistent with the results of most previous studies of temporal generalization (Delgado & Droit-Volet, 2007; McCormack, Brown, Maylor, Darby, & Green, 1999; Wearden, 1992; Wearden, Denovan, Fakhri, & Haworth, 1997; Wearden, Norton, Martin, & Montford-Bebb, 2007;



Standard = 400 msec

Standard = 4 sec

Figure 2. Proportions of *yes* responses (comparison duration = standard duration) plotted against comparison stimulus durations for the immediate, delay, and interference conditions, for the short (upper panel) and long (lower panel) duration ranges in Experiment 2.

Wearden & Towse, 1994), the generalization gradients were asymmetrical in the immediate condition, with the mean proportion of *yes* responses for longer comparison stimuli being significantly higher than that for comparison stimuli that were shorter than the standard durations [$t(29) = -6.97, p < .0001$]. There was also a similar asymmetry in the generalization gradients in the delay condition [$t(29) = -6.00, p < .0001$]. However, the asymmetry disappeared when this delay was filled with the interference task. In the interference condition, no difference was observed between the mean proportions of *yes* responses to comparison stimuli that were either shorter or longer than the standard duration [$t(29) = -1.49$, $p = .147$]. In addition, post hoc Scheffé tests indicated that the proportion of *yes* responses for shorter comparison stimuli was significantly higher in the interference condition than in both the immediate ($p = .001$) and the delay ($p = .012$) conditions, whereas there was no difference between the immediate and the delay conditions ($p = .747$). In contrast, no significant difference was observed between the three conditions for the proportion of *yes* responses for longer comparison stimuli [$F(2,89) = 1.47$, $p = .236$]. Overall, these results indicate that standard durations tend to be judged shorter with an interference task than without an interference task during the retention delay.

Modeling and Discussion

The results of Experiment 2 showed that the interference task, as compared with the other two conditions, gives rise to a type of shortening effect that suggests that participants tended to underestimate the value of the standard duration more after the interference task than they did after an unfilled retention delay or no delay at all. Moreover, our results suggest that the effects of the interference task on participants' time estimations were statistically independent of the duration range: short (100–700 msec) or long (1–7 sec).

In order to identify the mechanisms underlying interference-related effects on time judgments in a generalization task, the data of the present experiment were modeled by using the MCG model employed by Ogden et al. (2008). According to this model, the duration of the just-presented comparison stimulus, t, is stored in working memory, whereas the standard duration is stored in reference memory as a Gaussian distribution, with a mean equal to the standard value and a coefficient of variation, c. For each trial, a value s^* was randomly chosen from this distribution. Thus, the higher the coefficient of variation, c, the greater the variability of the standard representation in memory, and the flatter the generalization gradient. More specifically, increasing the coefficient of variation c and holding the other parameters constant flattens the generalization gradient while retaining a low proportion of *yes* responses for the shortest stimulus durations. The coefficient of variation of the remembered duration therefore constitutes a sensitivity parameter, controlling the slope of the generalization gradient. If c is the first parameter in the model, the second parameter, originally proposed by McCormack et al. (1999) in their model, is memory distortion, q, which serves as a multiplier of the remembered standard duration. If $q = 1.0$, the standard value is correctly remembered. If $q < 1$ or $q > 1$, the standard value is recalled as being shorter or longer than it is in reality. Decreasing and increasing q shifts the generalization gradient toward the left or right, respectively. The effect on the generalization gradient of manipulating these different parameters is clearly illustrated in Droit-Volet, Clément, and Wearden (2001) and Droit-Volet and Izaute (2005). We may thus expect that the shortening effect produced by the interference task would be related to a distortion of the standard duration in reference memory, thus lowering the q parameter value.

However, shorter comparison durations may also be more likely to be judged as being equivalent to the standard duration when the level of participants' arousal increased during the testing phase, as compared with the learning phase. Indeed, it is well known that the level of arousal changes as a function of testing contexts. In that case, the internal clock would have run faster after the interference task, thus shifting the generalization gradient toward the left, as compared with that obtained in the immediate testing condition. Therefore, we also tested another model with a q parameter held constant at 1.0 (accurate representation of the standard duration in reference memory) and a "clock" parameter, which serves as a multiplier of t. However, this model did not fit our data well. Indeed, it tended to shift the peak of the generalization gradient toward the left, such that the comparison duration just shorter than the standard duration was more likely to be judged as being equivalent to the standard than was the comparison duration equal to the standard, without producing a similar proportion of *yes* responses for these two comparison durations. Furthermore, manipulating the value of the "clock" parameter did not allow us to distort the shape of the generalization gradient as found in our experiment (Figure 2). Consequently, we did not consider this "clock" parameter in our model.

Added to the two memory parameters c and q is a decisional parameter, b, and a parameter p for random responding. The model of the generalization task assumes that participants will respond *yes* when $|(s^* - t)/t| < b$. The threshold b also has represented as a Gaussian distribution, with a mean value b and a coefficient of variation held constant at $0.5b$. As shown by Wearden (1992), changing this last parameter does not affect the data. For each trial, a value b^* was randomly chosen from this distribution. Increasing the value of b increases the proportion of *yes* responses, especially for the longer stimulus durations, but without altering the general shape of the generalization gradient (see Droit-Volet et al., 2001). Since the proportion of *yes* responses is slightly greater for the long comparison stimuli than for the short ones, it results in a greater rightward skew with a higher b value. The final parameter, p, is the proportion of random responses provided in each trial, without reference to the stimulus duration value (i.e., *yes* and *no* responses are equally probable). Increasing p flattens the generalization gradient by increasing the proportion of *yes* responses for each nonstandard stimulus duration, including the shortest ones.

The model was implemented in a program written in Visual Basic 6.0 (Microsoft Corporation), and the three experimental testing conditions were simulated using 1,000 trials for each comparison stimulus. The four parameter values were varied over a wide range in order to obtain the best-fitting simulation for the data in terms of the mean absolute deviation (MAD), which was the sum of the absolute deviation between the data obtained in our experiment (Figure 2) and those derived from the computer simulation, divided by 7 (for a more detailed description of the procedure, see Wearden, 1992). Table 1 shows the parameter values derived from the best fits with this model (MAD < 0.05). Note that any attempts to reduce or

Table 1
Parameter Values Derived From the Best Fit of the Model With the Data Obtained in the Generalization Task for the Short (100- to 700-msec) and Long (1- to 7-sec) Duration Ranges in the Immediate, Delay, and Interference Conditions in Experiment 2

Duration Range	Testing Condition	c	q	b	p	MAD
100–700 msec	Immediate	0.19	1.05	0.36	0	0.02
	Delay	0.23	1.05	0.34	.11	0.03
	Interference	0.30	0.94	0.32	.23	0.02
1–7 sec	Immediate	0.19	1.0	0.30	0	0.02
	Delay	0.19	1.0	0.27	0	0.02
	Interference	0.22	0.9	0.30	0	0.03

Note—c, coefficient of variation for memory representation of standard duration; q, amount of distortion for memory representation of standard duration; b, threshold; p, probability of random responses; MAD, mean absolute deviation between theoretical and real data.

increase the value of one of the parameters increased the MAD between the real and theoretical data.

For the immediate testing condition, the parameter values thus obtained were consistent with those reported in previous generalization studies (e.g., Delgado & Droit-Volet, 2007; Droit-Volet & Izaute, 2005; Wearden, 1992; Wearden & Towse, 1994). In particular, the p value was null and the c value was 0.19, indicating that the participants did not respond at random and that their memory representation of the standard duration was poor. In addition, for the short duration range, the parameter q was greater than 1 (i.e., $q = 1.05$), suggesting that shorter durations were slightly overestimated, consistent with Vierordt's (1868) law. Be that as it may, the most systematic and important change in the parameter values was for the memory distortion parameter q, which was clearly lower in the interference condition (although not in the delay one) than in the immediate condition, for both the long and the short duration ranges. Furthermore, this decrease in the q value was similar for both the short and the long duration ranges (i.e., 0.11 and 0.10). This confirms that interference produces a subjective shortening effect of the standard duration in reference memory.

Moreover, the model tended to suggest that the interference task also flattened the generalization gradients by increasing the coefficient of variation of the temporal representation in reference memory (parameter c). However, this was above all true for the short duration range, since the increase in the c parameter was four times greater for the short duration range than for the long one (0.11 vs. 0.03). Thus, the interference task made the representations of standard durations lasting less than 1 sec fuzzier. This led participants to produce more judgment errors in the interference condition than in the immediate one, as revealed by the greater proportion of random responses in the former than in the latter (p parameter). In the 100- to 700-msec condition, the participants were unable to give a time judgment in almost one trial out of four ($p = .23$). Note that for the short duration range, the proportion of random responses was also higher in the delay condition than in the immediate one (.11 vs. 0), and the coefficient of variation for the temporal representation in reference memory was slightly higher (0.23 vs. 0.19). This can be explained by the fact that temporal discrimination was poorer for the short duration range than for the long one, as indicated by the significant interaction between stimulus duration and duration range. Consequently, we can assume that the interference task not only produced a shortening of the remembered duration, but also affected other aspects of time judgment (e.g., random responses) for shorter durations, the latter perhaps being related to the former.

Finally, although the threshold value b varied between the three testing conditions, the values were 0.32–0.36 in the short duration range and 0.27–0.30 in the long duration range, suggesting little systematic influence of condition. Nevertheless, the small decrease in b between the immediate and interference testing conditions for durations less than 1 sec (0.04) was consistent with previous studies showing that when the timing task is more difficult, participants adopt a low decision threshold and are thus more conservative in their time judgments (e.g., Droit-Volet & Izaute, 2005; Ferrara, Lejeune, & Wearden, 1997; Wearden & Grindrod, 2002). This is consistent with a higher number of random responses for the short duration range. In sum, Experiment 2 showed that the representation of duration in reference memory in a generalization task is disrupted more by 15 min of interference than by a simple 15-min delay. Our model suggests that a subjective shortening of the remembered standard duration can mainly be ascribed to this interference effect.

GENERAL DISCUSSION

Our experiments provide evidence that the maintenance of representations in temporal reference memory is unaffected by a simple retention delay (Experiment 1) in a generalization task, even when this delay is extended from 15 min to 24 h. This is true for different duration ranges that are either shorter (i.e., 100–700 msec) or longer (i.e., 1–7 sec) than 1 sec. In contrast, for these two duration ranges, the performance of an interference task during the 15-min retention delay was found to affect the generalization gradients by shifting them toward the left, in comparison with the immediate and delay conditions.

Our data thus revealed a major effect of interference on temporal performance in a generalization task, in the shape of a shift of the gradient toward the left, as compared with the immediate and delayed tests. There seem to be two potential explanations for this leftward shift in the generalization gradient. The first is that the interference task chosen in the present study (game of "Snakes and Ladders") increased participants' arousal level, thereby speeding up their internal clock during the test. Consequently, shorter comparison durations were more likely to be judged as being equivalent to the standard duration. However, this internal clock acceleration would have a multiplicative effect with stimulus duration value—that is, a relatively greater effect on long durations than on short ones (e.g., Burle & Casini, 2001; Wearden & Penton-Voak, 1995)—whereas our results showed that the proportion of *yes* responses for short comparison stimuli was significantly higher in the interference condition than in the immediate one. However, there was no difference between these two conditions for the long comparison stimuli. Nevertheless, the comparison stimulus durations for the short and the long duration range preserved proportionality. This means that a similar shift in the temporal generalization gradients supports a scalar timing shift. More convincingly, our modeling of data using a "clock" parameter did not fit our data well; indeed, it shifted the peak of the generalization gradient toward the left, without producing a distortion of the shape of the gradient similar to that found in the present study. Overall, this suggests that a change in participants' arousal level due to the interference task was probably not the main factor that explained the shift of the generalization gradient toward the left in the interference testing condition, as compared with the immediate or delayed tests.

A second more plausible explanation, and consistent with that put forward by Ogden et al. (2008), is that participants underestimated the standard duration after performing the interference task. A subjective shortening effect has often been observed in studies of short-term retention of duration in animals (e.g., Church, 1980; Kraemer, Mazmanian, & Roberts, 1985; Leblanc & Soffié, 2001; Spetch & Wilkie, 1983; Wilkie & Willson, 1990) and in humans (e.g., Guay & Bourgeois, 1981; Lieving, Lane, Cherek, & Tcheremissine, 2006; Wearden, Goodson, & Foran, 2007; Wearden, Parry, & Stamp, 2002). These findings suggest that, when the duration of an event is retained in short-term memory, it becomes shorter as the retention delay increases (generally from 1 sec up to 10 sec), probably because of a loss of pulses during the maintenance of the temporal representation in memory. For short retention delays, the shortening effect would be due to a distractive effect on the representation of the duration while it is actively maintained in memory until the temporal judgment is given. However, in the case of longer retention delays, the standard duration no longer needs to be actively maintained, since it has been learned and stored in long-term reference memory.

Contrary to short-term temporal memory, there has been little prior evidence of a shortening effect in temporal reference memory. The only evidence comes from studies recently conducted by Ogden et al. (2008, 2010), which showed marked shifts in temporal generalization gradients when a generalization test with another standard duration was inserted between two tests of the initial standard duration, relative to a control condition without the second generalization test. In our study, however, we used a nontemporal interference task rather than a temporal one. When we compare the data obtained in these two studies, the shortening of the remembered standard duration would appear to be greater with a temporal interference task than with a nontemporal one. More specifically, the participants remembered the standard duration as being 10% shorter than it actually was with the nontemporal interference task in the present study and 33%–35% shorter with the temporal interference task in Ogden et al.'s (2008) study (p. 1541). However, the latter did not use a learning phase to strengthen the trace of the standard duration in memory, as we did in our experiment. Furthermore, in their study, the representation of the standard duration in memory may have been overwritten by the second interfering standard duration, thereby hindering the judgment of similarity between the comparison durations and the initial standard duration. Consequently, participants may have based their time judgments on the representation of a new standard duration. Whatever the case may be, our findings for a nontemporal interference task and sub- and suprasecond durations contribute to the literature by showing for the first time that a 15-min nontemporal interference task performed immediately after the standard duration is learned produces a subjective shortening effect in long-term temporal memory, for both duration ranges used here.

As was suggested at the beginning of this article, the consolidation of information in memory is a prerequisite for its long-term retention. Memories take time to be fixed or consolidated and, consequently, remain vulnerable to disruption for a period of time after learning (Dudai, 2004; Lechner et al., 1999; McGaugh, 2000). Accordingly, the process associated with the formation of new memories retroactively interferes with previously formed ones that are still undergoing this process of consolidation, thus leading to forgetting (Wixted, 2004, 2005). If any new memories are formed while previously learned memories are being consolidated, one would not expect any forgetting-related effect on the latter. Conversely, the formation of new memories during the consolidation of recently formed memory traces should result in the deterioration of the latter. This is consistent with our study showing that an unfilled retention delay had little or no effect on time judgments in a generalization task, whereas a retention delay occupied by the formation of new memories (during the interference task) significantly disrupted the process of consolidation of temporal memory traces. The process of consolidation in memory appears to be relatively fast, taking only a few hours at most (Dudai, 2004; Rodriguez-Ortiz & Bermudez-Rattoni, 2007; Sara & Hars, 2006). However, further research is now needed to clarify how long after the learning phase we have to wait before the interference task ceases to have a deleterious effect. It should be remembered that in the present study, the interference task was performed immediately after the learning phase.

One may wonder whether the 24-h retention delay in the present study can reasonably be viewed as an unfilled delay, insofar as all participants necessarily carried out several daily-life activities during that delay. Put differently, the question here is how we actually define interference. From a methodological point of view, it is impossible to prevent participants from engaging in normal day-to-day activities during a 24-h period; and it is true that some of these daily activities may be relatively similar to the parlor game used as an interference task in our experiment. However, as was previously explained, in our interference condition, the interference task was performed immediately after the learning phase. Some studies have shown that the deterioration in memory consolidation is greater when the interference occurs just after the initial learning (Dewar, Garcia, Cowan, & Della Sala, 2009; see also McGaugh, 2000, for a review). In addition, even if there were some interfering activities during the 24-h retention delay, we failed to find any significant effect of this retention delay on participants' performance in a temporal generalization task. This suggests that the consolidation of temporal memories after learning takes only a few hours.

Finally, another question is why an interference task that affects the consolidation of temporal memories causes the duration to be underestimated. The present study did not allow us to reach any clear conclusions. Memory research, however, has shown that during consolidation, memories undergo qualitative changes with regard to their underlying neural representation that stabilize them and shield them from future interference (Dudai, 2004; McGaugh & Roozendaal, 2009). The neural reactivation of newly acquired memories is critical for their consolidation and, most probably, for their subsequent recall (e.g., Hoffman & McNaughton, 2002; Wilson & McNaughton, 1994). We may thus assume that in our study, in which the participants remained in the same experimental context, they reactivated the learned standard duration. The interference task may have affected the representation of duration during this reactivation process, thereby contributing to its distortion.

In conclusion, the present study is one of the first to try to manipulate the maintenance of duration representations in reference memory using a temporal generalization task. Our results did not highlight any significant effect of the 15-min and 24-h delays on participants' time judgments, except when they were given an interference task to perform immediately after initial storage of the standard duration. The interference task mainly produced a shortening effect, which, according to our model, can be explained by the fact that participants remembered the standard duration as being shorter than it actually was.

AUTHOR NOTE

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NOTE

1. Previous analyses revealed neither a significant main effect nor any interaction effect involving the button order factor. This factor was therefore not included in the statistical analyses.

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