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Short-term memory for event duration: Modality specificity and goal dependency

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Abstract Time perception is involved in various cognitive functions. This study investigated the characteristics of short-term memory for event duration by examining how the length of the retention period affects inter- and intramodal duration judgment. On each trial, a sample stimulus was followed by a comparison stimulus, after a variable delay period (0.5–5 s). The sample and comparison stimuli were presented in the visual or auditory modality. The participants determined whether the comparison stimulus was longer or shorter than the sample stimulus. The distortion pattern of subjective duration during the delay period depended on the sensory modality of the comparison stimulus but was not affected by that of the sample stimulus. When the comparison stimulus was visually presented, the retained duration of the sample stimulus was shortened as the delay period increased. Contrarily, when the comparison stimulus was presented in the auditory modality, the delay period had little to no effect on the retained duration. Furthermore, whenever the participants did not know the sensory modality of the comparison stimulus beforehand, the effect of the delay period disappeared. These results suggest that the memory process for event duration is specific to sensory modality and that its performance is determined depending on the sensory modality in which the retained duration will be used subsequently.

Keywords Temporal processing · Short term memory · Multisensory processing

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Introduction

Time perception involves multiple subprocesses, such as the measuring and encoding of event time, retaining it in memory, and retrieving and using it to inform further behavior. Much research has focused on whether there is a central clock system to which all time perception subprocesses refer or whether there are distributed clocks specific to each subprocess (Grondin, 2010; Ivry & Schlerf, 2008; Mauk & Buonomano, 2004; Nobre & O'Reilly, 2004). This question has been examined by comparing time perception in different sensory modalities, and the results thus far support the idea that the time perception process is specific to sensory modalities (Chen & Yeh, 2009; Lapid, Ulrich, & Rammsayer, 2009; Noulhiane, Pouthas, & Samson, 2009; Ortega, Lopez, & Church, 2009; Rattat & Picard, 2012; for a review, see Grondin, 2010, pp. 567–568). For example, auditory duration is perceived as being longer than visual duration, even at physically equal lengths (e.g., Wearden, Edwards, Fakhri, & Percival, 1998; Wearden, Todd, & Jones, 2006); this suggests that the pacemaker of the auditory clock has a higher refresh rate than the visual clock and that auditory and visual time perception hence refer to different clocks.

While various theories with regard to the mechanisms and neural basis of measuring and encoding processes have been proposed and examined (e.g., the scalar expectancy theory based on the internal pacemaker-counter model;

Buhusi & Meck, 2005; Gibbon, Church, & Meck, 1984; Wearden, 2004), it has not been well understood how time—and, more specifically, event duration—is retained in memory. Recently, however, an increasing number of studies have suggested an interest in an underlying memory component for event duration (Droit-Volet, Wearden, & Delgado-Yonger, 2007; Grondin, 2005; Nobre & O'Reilly, 2004). At the center of that interest is, as with the encoding and measuring process, whether memory vis-à-vis stimulus duration is specific to sensory modality or whether each modality uses a common memory system (Gamache & Grondin, 2010a, 2010b; Ogden, Wearden, & Jones, 2010; Penney, Gibbon, & Meck, 2000; Rattat & Picard, 2012). For example, Gamache and Grondin (2010b) showed that the accuracy of reproduction performance with regard to visual and auditory stimulus duration varied as the delay period between stimulus and reproduction increased. As well, Rattat and Picard (2012), using a dual-task paradigm, demonstrated that an auditory task that took place during the retention period impaired auditory duration discrimination, while a visual task impaired visual duration discrimination. These results imply that the memory process might be specific to sensory modality, analogous to the working memory composed of a visual sketchpad and auditory phonological loop (Baddeley, 1992).

Given the possibility that duration memory is sensory specific, another question arises: What is responsible for determining memory performance? In other words, is the input modality the only determinant of memory performance? Working memory studies have suggested that input modality, as well as the content of the input itself, regulates memory performance (de Gelder & Vroomen, 1997; Mastroberardino, Santangelo, Botta, Marucci, & Olivetti, 2008). Furthermore, Bueti and Walsh (2010) showed that duration memory, even when the stimulus is presented in the same modality, could be dissociated by whether the retained duration was used for perception or action. Thus, the duration memory might be determined, in part, depending on the goal for which it will be used.

In order to investigate the modality specificity and goal dependency of duration memory, the present study examined the distortion patterns of subjective duration during the retention period, in a comparison of inter- and intramodal duration.[1] Event duration is not retained veridically in memory; rather, it distorts during retention (Gamache & Grondin, 2010a). Wearden and his colleagues have repeatedly reported that subjective duration retained in short-term memory shortens as the delay period increases (i.e., *subjective shortening*; Wearden & Ferrara, 1993; Wearden, Goodson, & Foran, 2007; Wearden, Parry, & Stamp, 2002). In their well-designed experiments, a sample (first) stimulus and a comparison (second) stimulus were presented with a variable delay period (usually up to 10 s) between them; participants were then asked to determine which of the two had been presented for a longer period (or equal, in some conditions). The basic finding was that the probability of selecting the sample stimulus as being longer decreased as the delay period increased. Although these researchers observed subjective shortening with respect to visual and auditory duration (Wearden et al., 2007), quantitative differences have not yet been examined; in fact, the distortion patterns showed modality differences in part (e.g., Experiment 1 in Wearden et al., 2007). Therefore, it is still unclear whether the distortion patterns are comparable between the retention of visual and auditory duration. Furthermore, when auditory and visual duration are compared, if the distortion patterns are found to be different, the distortion patterns for intermodal duration comparison would help examine whether it is only the input modality (i.e., the sensory modality of the retained stimulus) that is responsible for memory performance.

The present study investigated how visual and auditory duration is retained in short-term memory. More specifically, it examined whether distortion patterns of stimulus duration, as retained in short-term memory, depend on sensory modality. For this, a delayed matching paradigm was used, and the effect of the delay period on a duration comparison task was examined. In the experiments, a sample stimulus was presented in vision or audition, and it was subsequently compared with another visual or auditory stimulus presented after a variable delay period. We presented a variable duration of the sample stimulus so that the participants would encode the duration of the stimulus trial by trial; otherwise, the effects of delay period could not be examined. If the distortion patterns during the delay period were different among modality conditions, it would imply that the memory for duration might be specific to sensory modality. Furthermore, this study also examined whether or not the distortion pattern depends on the sensory modality of the sample or comparison stimulus.

Experiment 1A

Method

Fifteen undergraduate students participated as paid volunteers. All had reported normal or corrected-to-normal vision and normal hearing.

Visual stimuli were presented on a 21-in. CRT monitor (85 Hz; viewing distance, 57 cm). A white disk (3.9°, 77 cd/m^2) was presented at the center of a gray background (35 cd/m^2). On each trial, the first visual stimulus (sample stimulus)

[1] We mean by *goal dependency* that the memory process is determined depending on the sensory modality in which the retained duration will be used subsequently.

was presented after a 500-ms blank display, followed by a blank display (delay period) of variable duration and the second visual stimulus (comparison stimulus). After the comparison stimulus disappeared, each participant was asked to select which of the sample and comparison stimuli was presented for a longer period, by pressing the “1” or “2” key. The next trial began immediately after the participant responded. The duration of the sample stimulus was 765, 882, 1,000, or 1,118 ms, while the duration of the comparison stimulus was 0, 59, 118, or 235 ms longer or shorter than the sample duration. The duration of the delay period between the offset of the sample stimulus and the onset of the comparison stimulus (interstimulus interval; ISI) was randomly chosen, from 0.5, 1, 2, 3, 4, or 5 s. In total, 504 trials were conducted in a random sequence.

To examine distortion patterns during the retention period, the present study made use of a method of constant stimuli and compared the subjective duration of a sample stimulus among different ISI conditions. The probability of selecting the comparison stimulus as being longer was fitted by a cumulative Gaussian function, as a function of the difference in the comparison and sample durations for each ISI and each participant.[2] The point of subjective equality (PSE) was defined as the mean of the fitted Gaussian function; it indicates the difference in comparison duration from the sample duration, such that the sample and comparison stimuli are perceived as being of equal length. A larger PSE indicates that the comparison duration needs to be longer than the sample duration, if they are to be perceived as being of equal length.

Results and discussion

The left panel of Fig. 1 shows the PSE as a function of ISI. A one-way repeated measures ANOVA revealed a significant main effect of ISI, $F(5, 70) = 9.32$, $p < .001$, $\eta_p^2 = .40$. A multiple comparison (Ryan’s method) revealed that a PSE with a 0.5-, 1-, or 2-s ISI was significantly larger than that with a 3-, 4-, or 5-s ISI. These results showed that the length of delay period systematically affected comparisons of visual duration; generally, the PSE was smaller for longer delay periods, as compared with those for shorter delay periods. These results are consistent with the subjective shortening reported by Wearden and colleagues (Wearden & Ferrara, 1993; Wearden et al., 2002, 2007).

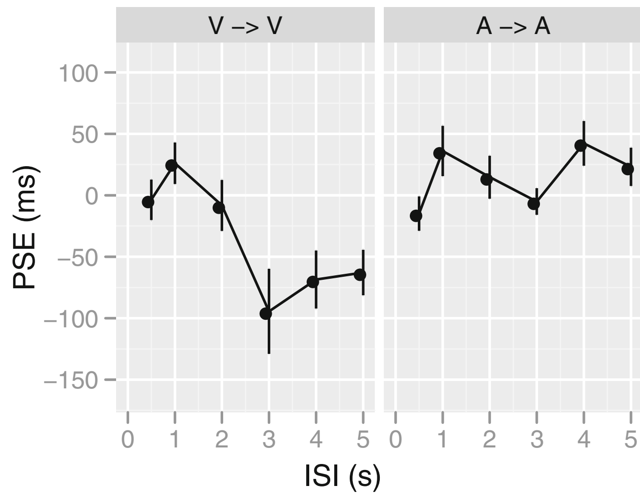

Fig. 1 Point of subjective equality (PSE) as a function of interstimulus interval (ISI) in Experiments 1A (left) and 1B (right). Error bars indicate the standard errors of the means (V = visual; A = auditory)

Experiment 1B

Method

Sixteen undergraduate students participated as paid volunteers. All had reported normal or corrected-to-normal vision and normal hearing. The methods and procedures were identical to those of Experiment 1A, except that no visual stimulus was presented and the sample and comparison stimuli were presented in the auditory modality. The auditory stimulus was a meaningless, complex tone presented via headphones.

Results and discussion

The right panel of Fig. 1 shows the PSE as a function of ISI. A one-way repeated measures ANOVA showed a significant main effect of ISI, $F(5, 70) = 4.38$, $p < .01$, $\eta_p^2 = .23$. A multiple comparison (Ryan’s method) revealed that a PSE with a 0.5-s ISI was considered smaller than those with a 1- or 4-s ISI; also, a PSE with a 3-s ISI was significantly smaller than that with a 4-s ISI. Thus, although the delay period was found to affect the PSE significantly, the effects were not at all systematic or, more importantly, qualitatively different from those in Experiment 1A. Unlike visual duration comparisons, the distortion pattern indicated that the systematic shortening of subjective duration did not take place during auditory duration comparisons. A between-experiment comparison determined that the delay period variously affected visual and auditory duration comparisons. A mixed two-way ANOVA revealed a significant interaction of ISI and stimulus modality, $F(5, 145) = 7.39$, $p < .001$, , $\eta_p^2 = .20$). Thus, the results showed the modality specificity of the distortion

[2] The psychometric function was estimated by using a generalized linear model (GLM), wherein the dependent variable was the binary response code (sample was longer or comparison was longer), the independent variable was the difference of sample and comparison durations, the error distribution was binomial, and the link function was probit (i.e., inverse cumulative Gaussian). Four different durations of sample stimuli were aggregated.

patterns; more specifically, the retained duration shortened only when stimuli were presented visually.

Experiment 2

The results of Experiment 1 showed that a shortening of subjective distortion took place with visual duration comparisons. However, it is unclear whether the sample or the comparison stimulus, or both, was responsible for that distortion. Experiment 2 examined the distortion patterns among intermodal (i.e., visual–auditory and auditory–visual) duration comparisons. If the input modality—namely, the sensory modality of the sample stimulus—was found to be responsible for distortion patterns, it would be expected that a shortening of subjective duration would take place in the pair featuring a visual sample stimulus and an auditory comparison stimulus.

Method

Fourteen undergraduate students participated as paid volunteers. All had reported normal or corrected-to-normal vision and normal hearing. The methods and procedures were identical to those of Experiment 1, except on the following points. In Experiment 2, in one session, the sample stimulus was visual, and the comparison stimulus was auditory (VA condition). In the other session, the sample stimulus was auditory, and the comparison stimulus was visual (AV condition). The order of the conditions was counterbalanced among the participants. The participants took a short rest before each session and were explicitly instructed about the stimulus modality presented in the session. The duration of the comparison stimulus was 0, 71, 141, or 282 ms longer or shorter than that of the sample stimulus, and the delay period was either 1 or 4 s. In total, 448 trials were conducted. The stimulus sequence was randomly determined in each block.

Results and discussion

Figure 2 shows the PSE as a function of ISI; the two modality conditions are shown separately. A two-way repeated measures ANOVA showed significant main effects of ISI, $F(1, 13) = 5.19$, $p < .05$, $\eta_p^2 = .29$, and stimulus modality, $F(1, 13) = 5.24$, $p < .05$, $\eta_p^2 = .29$, and also a significant interaction thereof, $F(1, 13) = 8.20$, $p < .05$, $\eta_p^2 = .39$. Since a significant interaction was found, we further examined whether the effects of ISI were significant in the AV and VA conditions separately. These analyses showed that the effect of ISI was significant only in the AV condition, $F(1, 13) = 7.51$, $p < .05$, $\eta_p^2 = 0\ .37$, while it was not significant in the VA condition, $F(1, 13) = 0.01$, $p = .91$, $\eta_p^2 = .00$.

These results suggested that the delay period affects PSE differently between the VA and AV conditions. In the VA condition—where visual duration was retained and compared with the subsequent auditory duration—the delay period had little to no effect on PSE. On the other hand, in the AV condition—where auditory duration was retained and compared with the subsequent visual duration—the PSE with a 4-s ISI was significantly smaller than that with a 1-s ISI. The distortion pattern in the AV condition was consistent with that in Experiment 1A, where both sample and comparison stimuli were presented visually. On the other hand, the distortion pattern in the VA condition was consistent with that in Experiment 1B, where both sample and comparison stimuli were presented in the auditory modality. These results suggested that the sensory modality of the comparison stimulus, and not the sample stimulus, was responsible for the shortening of subjective duration.

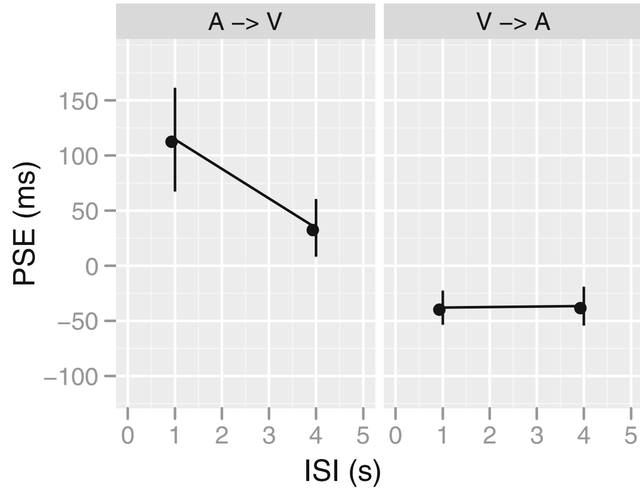

Fig. 2 Point of subjective equality (PSE) as a function of interstimulus interval (ISI) in Experiment 2. Error bars indicate the standard errors of the means (V = visual; A = auditory)

It was also found that the PSE in the AV condition was larger than that in the VA condition, irrespective of delay period. This suggested that the visual duration needed to be longer than the auditory duration, if the two were to be perceived as being equal in length. In other words, the auditory duration was judged to be longer than the physically equal visual duration. Note that this asymmetry cannot serve as evidence of differential memory processes in the VA and AV conditions; rather, the asymmetry resulted from differences in the measuring or encoding processes, since many studies (e.g., Wearden et al., 1998) have found this type of audiovisual asymmetry in undertaking duration comparisons.

Experiment 3

Taking the results of Experiments 1 and 2 together, we hypothesized that the sensory modality of the comparison stimulus is responsible for the memory performance of stimulus duration. However, different sets of individuals participated in Experiments 1A, 1B, and 2. Given that time perception is susceptible to large individual differences (Rammsayer, 1997; Westfall, Jasper, & Zelmanova, 2010), the present study's hypothesis would be more plausible if these results were replicated by directly manipulating only the sensory modality of the comparison stimulus and by examining the distortion patterns within the same individuals. Therefore, an additional experiment was conducted, where visual duration was retained and compared with either visual or auditory duration, thus allowing for an examination of the effect of delay period on PSE within the same individuals.

Method

Thirteen undergraduate students participated as paid volunteers. All had reported normal or corrected-to-normal vision and normal hearing. The methods and procedures were identical to those in Experiment 2, except that the sample stimulus was a visual stimulus on every trial and the comparison stimulus was either a visual (VV condition) or an auditory (VA condition) stimulus. These two conditions were conducted in separate sessions, and the participants were given explicit instructions vis-à-vis the modality condition before the sessions. The order of the conditions was counterbalanced among the participants.

Results and discussion

Figure 3 shows the PSE as a function of ISI; the two modality conditions are shown separately. A two-way repeated measures ANOVA revealed a significant main effect of ISI, $F(1, 12) = 11.2$, $p < .01$, $\eta_p^2 = .48$, and stimulus modality, $F(1, 12) = 6.43$, $p < .05$, $\eta_p^2 = .35$, and also a significant interaction thereof, $F(1, 12) = 16.3$, $p < .01$, $\eta_p^2 = .58$. Since a significant interaction was found, we further examined whether the effects of ISI were significant in the VV and VA conditions separately. These analyses showed that the effect of ISI was significant only in the VV condition, $F(1, 12) = 18.2$, $p < .01$, $\eta_p^2 = .60$, and not in the VA condition, $F(1, 12) = 0.07$, $p = .80$, $\eta_p^2 = .01$. Thus, the distortion patterns in the VV condition were similar to those in the visual condition in Experiment 1A and those in the AV condition in Experiment 2. On the other hand, the distortion pattern in the VA condition—wherein the delay period had little to no effect on PSE—was similar to those in the auditory condition in Experiment 1B and those in the VA condition in Experiment 2. Thus, the results of Experiments 1 and 2 were replicated by manipulating only the sensory modality of the comparison stimulus within the same individuals. These results further support the hypothesis that the sensory modality of the comparison stimulus is responsible for the delay period effect.

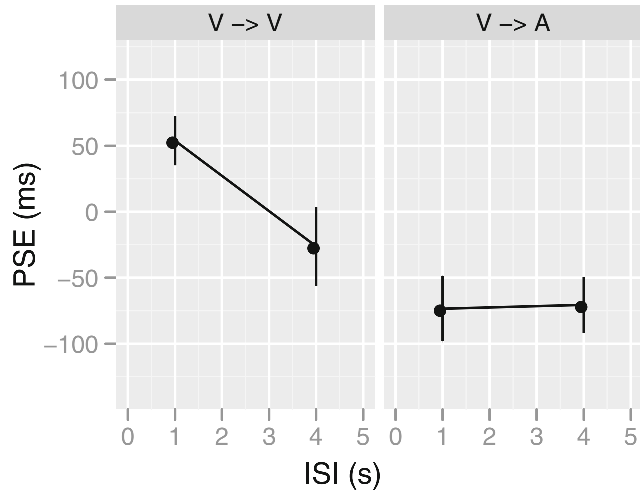

Fig. 3 Point of subjective equality (PSE) as a function of interstimulus interval (ISI) in Experiment 3. Error bars indicate the standard errors of the means (V = visual; A = auditory)

Experiment 4

In Experiments 1A, 1B, 2, and 3, the modality conditions were blocked, and hence, the participants knew the sensory modality of the comparison stimulus, both when the sample stimulus was presented and while they retained the duration of the sample stimulus. This means that the participants could control the memory process, on the basis of the expected sensory modality of the comparison stimulus. If this were indeed the case, what would happen if the sensory modality of the comparison stimulus was uncertain during the delay period? To answer this question, an experiment was conducted where the modality of the comparison stimulus was randomly determined trial to trial and, hence, the participants could not know the sensory modality of the comparison stimulus when the sample stimulus was presented and during the delay period.

Method

Thirteen undergraduate students participated as paid volunteers. All had reported normal or corrected-to-normal vision and normal hearing. The methods and procedures were identical to those in Experiment 3, except that the VV and VA conditions were presented randomly for each trial; hence, the participants were unable to know the modality of the comparison stimulus until it was actually presented.

Results and discussion

Figure 4 shows the PSE as a function of ISI; the two stimulus modality conditions are shown separately. A two-way repeated measures ANOVA revealed a significant main effect of stimulus modality, $F(1, 12) = 7.11$, $p < .05$, $\eta_p^2 = .37$.

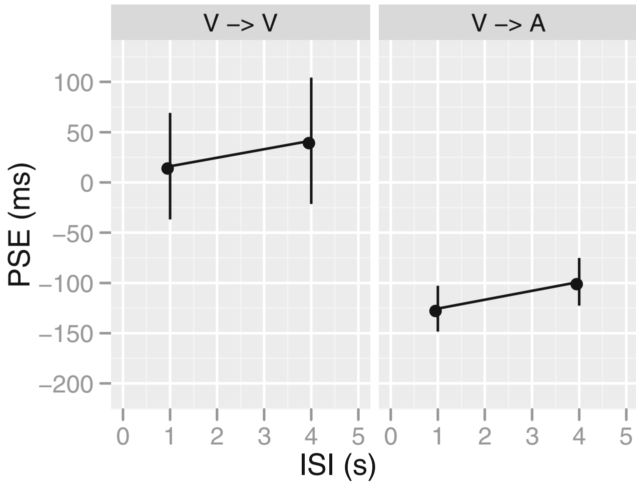

Fig. 4 Point of subjective equality (PSE) as a function of interstimulus interval (ISI) in Experiments 4. Error bars indicate the standard errors of the means (V = visual; A = auditory)

However, unlike in Experiment 3, neither the main effect of ISI, $F(1, 12) = 2.50$, $p = .13$, $\eta_p^2 = .17$, nor, more importantly, the interaction between that modality and the ISI effect, $F(1, 12) = 0.00$, $p = .98$, $\eta_p^2 = .00$, was significant. Thus, even when the comparison stimulus was visually presented, the effect of the delay period on PSE disappeared whenever the participants had been unable to know the modality of the comparison stimulus beforehand. In other words, it is not the presentation of the comparison stimulus in the visual modality but the expectation of a comparison stimulus being presented visually that produces the effect of the delay period on the subjective duration of memory vis-à-vis a sensory event.

General discussion

The present study investigated how the delay period affects inter- and intramodal duration comparisons. The observations thereof are summarized as follows: (1) The PSE was smaller for longer delay periods, as compared with shorter delay periods, when the comparison stimulus was visually presented; (2) the PSE distortion patterns due to the delay period occurred irrespective of the sensory modality of the sample stimulus; and (3) the delay period affected the PSE only when the participants could know beforehand that the sensory modality of the comparison stimulus was visual.

The main purpose of the present study was to examine whether the memory process for duration was separable, depending on the sensory modality of the stimulus, and, if so, whether the modality of the sample stimulus or of the comparison stimulus was responsible for the memory distortion. The results suggested that the delay period variously affected the duration judgment depending on the sensory modality of the comparison stimulus, irrespective of that of the sample stimulus. When the comparison stimulus was visually presented, the subjective duration of the sample stimulus shortened as the delay period increased; additionally, the effects were quantitatively and qualitatively similar between the visual sample stimulus (i.e., intramodal judgment; Experiments 1A and 3) and the auditory sample stimulus (i.e., intermodal judgment; Experiment 2). On the other hand, the delay period had little to no effect on duration judgment when the comparison stimulus was auditory (Experiments 1B, 2, and 3). These results support the idea that the process involved in remembering duration is separable, depending on sensory modality (Chen & Yeh, 2009; Grondin, 2003; Lapid et al., 2009; Noulhiane et al., 2009; Ortega et al., 2009; Rattat & Picard, 2012). They also imply that the memory process used for duration judgment might depend on how the retained duration is used (Bueti & Walsh, 2010).

It has been discussed for some time whether the internal clock is specific to certain sensory modalities (Noulhiane et al., 2009; Ortega et al., 2009; for a review, see Grondin, 2010). A number of studies have shown a difference in time resolution (Grondin, 2003; Grondin & McAuley, 2009) or in subjective duration for a physically equal duration (Wearden et al., 1998) among different sensory modalities, leading to the idea of distributed internal clocks in the brain. Likewise, it was found that the duration of an auditory stimulus was perceived as being longer than that of a visual stimulus in an intermodal duration comparison (Experiments 2, 3, and 4). Perhaps sensory specificity in the measuring process (e.g., the ticking duration of an external event using a sensory-specific pacemaker) is responsible for these asymmetric duration perceptions.

Furthermore, the overall results also suggested that the memory process is specific to sensory modality. It was found that the effect of the delay period varied, depending on the combination of the sensory modalities of sample and comparison stimuli. Recently, some studies have focused on the relationship between memory for duration and sensory modality by examining the effect of the delay period on the variability of task performance (Gamache & Grondin, 2010a, b; Ogden et al., 2010; Rattat & Picard, 2012). Although not conclusive, the results of these studies suggest that the variability of memory for duration is separable for different sensory modalities (Gamache & Grondin, 2010b; Rattat & Picard, 2012). The results of the present study, in demonstrating that the effect of the delay period on subjective duration also depended on sensory modality, provide further evidence that supports the idea that the memory process for duration is specific to sensory modality. Given the number of studies suggesting that the accuracy in duration comparison was different depending on the pairs of sensory modalities to be compared (Grondin, 2003; Grondin & McAuley, 2009), the sensory specificity of the memory process might originate from the differences in the temporal resolution. It is worthwhile to note that this idea does not necessarily indicate that different components (i.e., different brain regions) serve as visual and auditory memory centers. Instead, the memory process might change one's behavior, depending on the sensory modality. Further neuroimaging research would be informative and clarify the neural mechanism(s) of the sensory specificity of duration memory (N'Diaye, Ragot, Garnero, & Pouthas, 2004; Shih, Kuo, Yeh, Tzeng, & Hsieh, 2009).

Besides the sensory specificity of duration memory, the results of the present study also suggested that the sensory modality of the comparison stimulus was responsible for the effect of the delay period. When the comparison stimulus was visually presented, the PSE was shortened as the delay period increased, irrespective of the modality of the sample stimulus. The delay period had little to no effect on the auditory comparison stimulus. Considering that the duration of the sample stimulus had been retained, these results seemed to be somewhat counterintuitive. It was conjectured that perhaps the memory process for event duration would be flexible, depending on the goal underpinning the retained duration. For example, Bueti and Walsh (2010) recently showed that memory for duration was separable, depending on the type of subsequent task for which the duration was used. In their experiments, participants conducted action or perception tasks in separate blocks. The participants retained a sample duration, and after the variable delay period, they performed time reproduction in the action task and time comparison in the perception task. The results showed that the delay period affected performance in those action and perception tasks in various ways, implying that duration memory might be sensitive to how that retained information will be used later.

Furthermore, in Experiment 4 of the present study—where the sensory modality of the comparison stimulus was uncertain—the modality specificity of the distortion pattern disappeared, and the distortion patterns in both the visual–auditory and visual–visual conditions were similar to those in the auditory condition. In other words, the sensory modality of the comparison stimulus cannot be responsible for memory performance without its being known beforehand. Instead, since the auditory memory for time is more robust than the visual memory for time (Grondin, 2003; Grondin & McAuley, 2009), a duration comparison might take place in the auditory domain. For example, Grondin and McAuley showed that the duration comparison was accurate for an auditory–auditory pair, auditory–visual or visual–auditory pairs, and a visual–visual pair, in that order. This would imply that it is the best strategy to compare two durations in auditory domain.

Apart from the memory process discussed here, the distortion of subjective duration has been widely observed with an oddball or stimulus repetition paradigm. For example, unexpected stimuli are perceived as longer, while the repeated stimuli are perceived as shorter (Matthews, 2011; Pariyadath & Eagleman, 2007; Tse, Intriligator, Rivest, & Cavanagh, 2004; Ulrich, Nitschke, & Rammsayer, 2006). In these researches, the distortion is attributed to attention (Tse et al., 2004), predictability or novelty (Matthews, 2011; Pariyadath & Eagleman, 2007), or change of the speed of the internal pacemaker (Ulrich et al., 2006). Meanwhile, the contribution of the memory component has been much less discussed. However, the oddball and repetition tasks necessarily involve the memory process, since the duration of a target stimulus was tested against the duration of the other stimuli stored in memory. Therefore, given a number of studies indicating temporal distortion in the memory process, the distortion in the oddball or stimulus repetition may be reconsidered in the context of the distortion in memory. More specifically, the distortion in memory may also contribute to the distortion in oddball or stimulus repetition.

The distortion patterns observed in the present study are partially consistent with those among the previous findings of Wearden and his colleagues (Wearden & Ferrara, 1993; Wearden et al., 2002, 2007). They reported that the retained duration shortened as the delay period increased (subjective shortening). However, they also reported that subjective shortening took place even in the auditory domain—that is, with an auditory sample and comparison stimuli (Wearden et al., 2007). Although it is not clear why subjective shortening was not observed in the auditory domain in the present study, there are potential differences that might induce the inconsistency, such as stimuli, procedures, measurements, and analyses.[3] The most likely cause of the inconsistency would be the difference in the range of sample durations. Wearden and his colleagues repeatedly reported subjective shortening by using a short duration for the sample stimulus—up to 650 ms. Meanwhile, when sample stimuli of longer duration were used, they also reported that subjective shortening was absent (e.g., Droit-Volet et al., 2007; sample duration was between 1,200 and 2,000 ms). Thus, subjective shortening seems to be robust when short durations are retained. The sample duration in the present study was 765–1,118 ms, which was in between Wearden et al.'s short and long sample durations, and hence we did not observe subjective shortening in the auditory domain. These results suggest that retention of short and long durations is mediated by qualitatively different processes (Grondin, 2012).[4] In addition, the boundary between short and long may depend on sensory modality; the auditory boundary is shorter than the visual boundary, which would

[3] It is noteworthy that the method of measurements and analyses would not be responsible for the inconsistency, since our additional analyses following the Wearden et al. (2007) paper replicated the findings reported here, in which subjective shortening took place only for the visual comparison stimulus.

[4] The other relevant factor might be the time order error (TOE). It is known that the direction of the TOE depends on the duration of the first (sample) stimulus and that the boundary ranges around 1 s (Eisler, Eisler, & Hellström, 2008).

be consistent with the finding that the estimated durations of sounds are longer than those of lights (Wearden et al., 1998). Systematic investigation on subjective shortening by using a broader range of sample duration warrants these hypotheses.

In conclusion, the results of the present study support the idea that memory performance for duration is specific to sensory modality. Furthermore, these results also suggest that memory performance is determined depending on the sensory modality of the comparison stimulus, pointing to the possibility that the memory process for event duration is more complicated and flexible than had previously been considered. We will address two issues for future research. First, the memory process for duration information should be investigated systematically by using a wider range of the retained (sample) deration. Taking Wearden and his colleagues' study and our study together, the memory process for the shorter and longer duration may behave differently (see also Grondin, 2012), and the boundary of the short and long durations may be specific to each sensory modality. Second, the implication of Experiment 4 should be extended. It was suggested that the modality for duration memory is determined depending on the sensory modality of the comparison stimulus—that is, how the retained duration will be used subsequently. A focused investigation of the uncertainty of the comparison stimulus (e.g., manipulating the reliability of the cue indicating the modality of comparison stimulus) will provide clear and direct evidence regarding how the memory process is determined in a more naturalistic situation.

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