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Are memories for duration modality specific?

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Four experiments examined the effects of encoding multiple standards in a temporal generalization task in the visual and auditory modalities both singly and cross-modally, using stimulus durations ranging, across different experiments, from 100 to 1,400 ms. Previous work has shown that encoding and storing multiple auditory standards of different durations resulted in systematic interference with the memory of the standard, characterized by a shift in the location of peak responding, and this result, from Ogden, Wearden, and Jones (2008), was replicated in the present Experiment 1. Experiment 2 employed the basic procedure of Ogden et al. using visual stimuli and found that encoding multiple visual standards did not lead to performance deterioration or any evidence of systematic interference between the standards. Experiments 3 and 4 examined potential cross-modal interference. When two standards of different modalities and durations were encoded and stored together there was also no evidence of interference between the two. Taken together, these results, and those of Ogden et al., suggest that, in humans, visual temporal reference memory may be more permanent than auditory reference memory and that auditory temporal information and visual temporal information do not mutually interfere in reference memory.

Keywords: Timing; Temporal generalization; Interference; Modality; Reference memory.

The leading theory of time perception, *Scalar Expectancy Theory* (SET: Gibbon, Church, & Meck, 1984) and its associated information-processing model, suggests that timing is achieved via the combined function of a pacemaker-accumulator clock, memory processes, and a decision strategy. Memory processes are further split into short-term and reference memory

stores, with reference memory being responsible for the storage of “important times” (Church & Gibbon, 1982). Important times can be the time of reinforcement in animal studies or the standards in psychophysical tasks with humans. In the mathematical incarnation of the SET information-processing system (Church, 1984) durations are encoded into reference memory from short-term

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memory via a multiplicative transform K^* (Meck, 1983). K^* varies as a Gaussian distribution with a mean of 1 and some standard deviation. Each time a duration is transferred from short-term memory to reference memory a new value is drawn from the distribution to be multiplied by the contents of short-term memory and encoded in reference memory (for a more extensive discussion, see Jones & Wearden, 2004).

A key question in the literature is whether stimuli presented in different modalities—for example, auditory or visual—are timed and stored in the same way. For example, is there one reference memory that stores durations derived from stimuli in different modalities, or are there separate storage methods or even distinct brain areas for the processing of the duration of stimuli of different modalities? First, let us consider the known differences between the timing of stimuli in different modalities. A robust finding within the timing literature is that “sounds are judged longer than lights” (Behar & Bevan, 1961; Goldstone, Boardman, & Lhamon, 1959; Goldstone & Lhamon, 1974; Wearden, Edwards, Fakhri, & Percival, 1998). That is, there is a subjective difference in the perception of the duration of auditory and visual stimuli of the same objective duration, with auditory stimuli appearing to last for longer than visual stimuli. One explanation is that this effect occurs primarily because of differences in the operation of the pacemaker of the internal clock, with faster pacemaker speeds for auditory stimuli than for visual stimuli (Wearden et al., 1998).

A faster clock speed is suggested by the multiplicative effect that is observed in auditory/visual comparisons. When participants estimate the duration of various auditory and visual stimuli, the degree of overestimation of the auditory stimuli compared to the visual ones increases as the duration of the stimuli increases: In other words the effect manifests itself as a slope rather than an intercept difference in the function relating mean duration estimate to objective duration (see Wearden et al., 1998). Explanations of the differences between the timing of auditory and visual stimuli that are based on differing pacemaker

speed only tell us that what is put into reference memory (clock output) is different for different modalities; they do not address how modality differences may manifest themselves in memory. Penney, Gibbon, and Meck (2000) suggest that in addition to a faster pacemaker speed for auditory stimuli, “memory mixing” is also required for modality differences to be manifested in behaviour. Penney et al. (2000) suggest that a duration presented in both modalities will mix in reference memory resulting in the standard being remembered as being somewhere in between the value produced by the faster auditory clock and the slower visual clock. As a result of this mixing all subsequent auditory stimuli of the same duration as the standard will be judged as longer than the standard whereas visual stimuli of the same duration will be judged to be shorter.

The idea of memory mixing was suggested because modality effects have most frequently been demonstrated when both auditory and visual stimuli were experienced by the same participants in an experimental session. However, Wearden, Todd, and Jones (2006) showed that modality differences could still be observed when only one modality was experienced, suggesting that memory mixing is not a necessary condition to produce modality differences in duration judgments, although it may be sufficient to produce them. Furthermore, the size of the modality difference was no greater when people received both auditory and visual stimuli, thus allowing memory mixing to be potentially present, compared with when they received only one stimulus type, and memory mixing could not occur.

Whilst it is clear that the primary cause of auditory/visual modality differences in timing might be the difference in the clock speed for the two stimulus types, the work of Penney et al. (2000) and Wearden et al. (2006) demonstrates the need for more research examining the similarities and differences in the way durations of stimuli in different modalities are stored in reference memory. Previous research has demonstrated comparable effects of cholinergic drugs, which are known to affect reference memory function in animals, on auditory, visual, and tactile peak

interval (PI) tasks (Meck, 1983, 1987; Meck & Church, 1987a). Disruption or damage to cholinergic pathways in the brain has also been shown to affect the functioning of reference memory in the same way for auditory and visual stimuli in rats (Meck, Church, & Wenk, 1986; Meck, Church, Wenk, & Olton, 1987; Meck & Williams, 1997; Olton, 1989). Although these results suggest comparable processing for the duration of stimuli in different modalities, it should be noted that experiments involving animals use very different procedures, and different time ranges, from those used in studies with humans, so generalization of the findings to situations where humans time brief intervals may be questionable. In human timing, however, the well-documented effects of human ageing on timing have also been found to be comparable in auditory and visual timing (Droit-Volet, 2002; Droit-Volet, Clément, & Wearden, 2001; Droit-Volet & Wearden, 2001; McCormack, Brown, Maylor, Darby, & Green, 1999; McCormack, Brown, Maylor, Richardson, & Darby, 2002; Wearden, Wearden, & Rabbitt, 1997).

Although the effects on timing produced as a result of brain damage, drug, and age manipulations do not appear to differ between modalities, it is possible that this is because these variables exert a global effect on reference memory rather than localized effects on some of the stimuli within it. If we were to imagine reference memory as a pool, which may have different areas for different types of information, then it is possible that there will be some manipulations that will lead to changes in everything in the pool, regardless of what the contents are. For example, a drug manipulation may affect everything which enters reference memory because it affects the value of K^* . However, it is also possible that some manipulations will only affect some of elements within the pool, or that different areas of the pool will interfere with each other under some circumstances.

A small body of research has studied the effects of increasing reference memory load on visual timing performance. A series of studies by Brown (Brown, 1997, 1998; Brown, Stubbs, &

West, 1992; Brown & West, 1990) examined performance on a number of tasks when more than one visually presented interval was simultaneously timed. Using reproduction, production, and verbal estimation methods Brown found that timing multiple stimuli resulted in increased variability in timing, and he suggested that the division of attention between each stimulus resulted in more variable timing.

Jones and Wearden (2004) also examined the effects of encoding more than one standard in reference memory using a modified temporal generalization task. To prevent poorer performance due to demands on attention causing disruption at encoding Jones and Wearden (2004) presented all stimuli separately, rather than simultaneously as in the Brown studies. Two standards of different duration were presented, one high in pitch and the other low in pitch, and comparison durations for each of the standards were presented in the same pitch as the standard to be used for the comparisons. Participants had to compare each comparison tone with the corresponding standard and judge whether or not they were of equal duration. In some of their experiments participants were only tested on one standard, whilst in others they were tested on both, but in either case they did not know which they would be tested on at the time of encoding; thus regardless of the experimental conditions both standards were always encoded. Memory loading effects resulting in an increase in the variability of the representation of the standard in reference memory were only found when participants were tested on both standards. This result implies that simply encoding more than one standard has no effect on performance, although encoding multiple standards that are used at a later point does result in more variable task performance.

Increased memory load has also been examined across modalities. Grondin (2005) conducted a similar study to that of Jones and Wearden (2004), but using a bisection method rather than generalization. Interestingly, Grondin (2005) found that increasing the potential processing load of the standards used by presenting them in different modalities (auditory and visual) did not affect

performance, suggesting that presenting the same standard in multiple modalities does not affect its encoding. Grondin (2005) suggested that the absence of a modality effect indicates that the same representation is used for auditory and visual stimuli in reference memory; thus there is no increase in memory load when standards are presented in two modalities rather than one. Poorer task performance when multiple modalities are used within a trial has, however, been reported when more than three marker types (auditory, visual, and electro-tactile) were used to mark the start and end of unfilled durations (Grondin & Rousseau, 1991). In this case poorer performance is thought to be due to the effects of having to switch attention between different marker types, rather than increased memory load due to different representations of the marker for each modality.

Interference between stimuli of different durations but of the same modality has been examined by Ogden, Wearden, and Jones (2008). The aim was to see whether the relationship between the durations of multiple standards stored in reference memory at the same time would result in systematic interference, rather than just producing more variable performance. Ogden et al. (2008) used a modified temporal generalization method in which participants were presented with a first standard (A) and then had to compare its duration to eight comparison durations; the comparison duration that was equal to the standard was presented twice (A comparisons: *immediate testing of A*). Participants were then presented with a second standard (B) and had to compare its duration to eight comparison durations (B comparisons: *immediate testing of B*). B was longer than, shorter than, or the same duration as A. The A comparisons were then re-presented (without the re-presentation of A), and participants had to compare their duration with their memory of A. On some trials a delay of from 0 (*deferred retesting*) to 30 s (*delayed retesting*) was imposed after the last comparison for B and prior to the retesting of A. Using this method the critical comparison of interest is between performance on the immediate testing of A and performance at deferred and delayed retesting.

In Ogden et al. (2008) and the current series of experiments, systematic interference as a result of the second standard could potentially manifest itself in three ways: All responding could become more variable in the deferred and delayed conditions by comparison to the immediate one, resulting in flatter temporal generalization gradients; multiple standards may mix in reference memory resulting in peak responding at a value in-between that of the encoded standards (as suggested by Penney et al., 2000); finally, instead of “mixing” the standards in reference memory, participants may contrast them inaccurately resulting in peak responding at durations much shorter or longer than those encoded as the standards.

Ogden et al. (2008) found that when A and B were different durations dramatic interference effects could sometimes be observed. For example, in their Experiment 2 when B was longer than A peak responding occurred at or around the comparison that had the same duration as the standard in immediate testing and in deferred retesting. In delayed retesting, however, the response peak occurred to the shortest of the comparison durations, which was identified as the standard on an average 82% of trials, suggesting that the standard was recalled as being shorter than it actually was. In their Experiment 3, Ogden et al. (2008) demonstrated that peak responding could also shift in the opposite direction. When B was shorter than A peak responding occurred at or around the standard in the immediate testing and deferred retesting conditions. However, in the delayed testing condition peak responding shifted to the longest of the comparison duration suggesting an increase in the duration of the standard in reference memory.

Ogden et al. (2008) suggest that the shifts in peak responding occurred because the memory of A was so degraded as to be useless. They proposed that in order to complete the task participants constructed a new standard on the basis of the relationship between A and B—for example, not remembering the exact duration of A but remembering that it was shorter than B and therefore only responding to comparisons that were shorter than B. This “construction” process is flawed so

A is constructed as being much shorter or longer than it actually was, resulting in the observed shifts in peak responding.

Having found such dramatic and systematic interference effects in reference memory with auditory stimuli the aim of the present work was to investigate whether the same effects would manifest when multiple duration standards derived from visual stimuli were stored in reference memory. In addition to this, other experiments examined the issue of whether auditory and visual standards could interfere with each other in reference memory. This also allowed examination of whether a subjective difference in duration (deriving from the fact that visual stimuli appear subjectively shorter than auditory ones of the same real duration) was sufficient to produce interference comparable to that seen when there was an actual difference in duration.

If auditory and visual stimuli do interfere with each other it would suggest that they are stored in similar ways in reference memory, supporting the idea that there is a single memory for temporal information derived from stimuli in different modalities. Alternatively, if the systematic interference observed with auditory stimuli is absent when visual stimuli are used, and when both auditory and visual stimuli are used in the same experiment, it would suggest that temporal stimuli of different modalities are stored separately or distinctly in reference memory. Establishing how stimuli of different modalities are stored in reference memory may thus clarify the causes of subjective differences in the timing of different stimuli. It will also illuminate similarities and differences between the operation of reference memory and more general nontemporal long-term memory.

EXPERIMENT 1

Experiment 1 attempted to replicate the systematic interference effects obtained by Ogden et al. (2008) with auditory stimuli, so as to provide a comparison with the results to be obtained using visual, or both visual and auditory, stimuli in later experiments. Experiment 1 therefore

employed the A–B–A interference paradigm developed in Ogden et al. (2008), in which participants were presented and tested on the first standard (A) and were then presented and tested on the second standard (B), which was always 400 ms longer than A. Finally participants' memory of A was retested after a delay of either 0 (deferred testing) or 30 s (delayed testing).

Method

Participants

A total of 13 University of Manchester students were paid £5 for participating. Payment was not contingent on performance.

Apparatus

An IBM-PC compatible computer recorded all experimental events. The stimuli whose durations were judged were always 500-Hz tones produced by the computer speaker. The keyboard monitored the participant's responses. The program that ran the experiment and recorded all the data was written in MEL language (Micro-Experimental Laboratory: Psychology Software Tools, Inc.).

Procedure

The variant of temporal generalization developed in Ogden et al. (2008) was employed using auditory stimuli. All stimuli were presented in one experimental session lasting approximately 20 minutes. Participants were instructed that they would be presented with a standard duration, in the form of a 500-Hz tone, and that they had to compare the standard with eight comparison durations, stating whether each comparison was the same duration as the standard or different (YES/NO response).

At the beginning of each block participants were presented with the standard duration three times. The duration of the standard was selected randomly from a uniform distribution ranging from 400 to 600 ms, but all three presentations had the same duration value. A delay drawn from a uniform distribution ranging from 1,500–2,000 ms occurred between each presentation of the standard. Participants were then

presented with eight comparison durations. The comparison durations were Standard A multiplied by 0.625, 0.75, 0.875, 1.00, 1.00, 1.125, 1.25, 1.375, presented in a random order (the comparison duration that was equal to the standard was presented twice). After each of the A comparisons, participants had to indicate whether the stimulus had the same duration as Standard A by pressing "Y" for yes and "N" for no on the keyboard. This is subsequently referred to as *immediate testing*. Following the final response to the A comparisons participants were presented with a standard B three times. B was always 400 ms longer than A. After the presentation of Standard B, eight comparison durations were presented (B comparisons). The B comparisons were Standard B multiplied by 0.625, 0.75, 0.875, 1.00, 1.00, 1.125, 1.25, 1.375, and they were presented in a random order. After each of the B comparisons participants had to indicate whether they were the same length as Standard B by pressing "Y" for yes and "N" for no on the keyboard. Finally, the A comparisons were presented again after a delay of either 0 (deferred testing) or 30 s (delayed testing). Standard A was not represented. Participants had to compare the A comparisons to their memory of Standard A. The above procedure was repeated six times, with a different duration for Standard A each time. No performance-related feedback was given. Figure 1 shows a diagram of the procedure.

Results

Figure 2 shows temporal generalization gradients in the usual form of the mean proportion of YES responses plotted against the comparison/standard ratio for each testing condition. Examination of Figure 2 suggests that the systematic interference effects observed in Ogden et al. (2008) were also present in the current experiment. As in Ogden et al. in immediate testing peak responding occurred at the standard. In deferred retesting gradients appeared slightly flatter, and in delayed retesting peak responding shifted to a comparison value much shorter than the standard. The peak was located at the comparison duration that was 75% of the standard

Figure 1. Schematic outline of the procedure for Experiment 1. Variants of this general procedure were used in most of the other experiments. See text for other details.

duration, but the next highest proportion of YES responses occurred to an even shorter comparison duration, the one that was 62.5% of the standard.

Figure 2. Temporal generalization gradients (proportion of YES responses—identifications of a comparison duration as the standard—plotted against comparison/standard ratio) from Experiment 1. Within each panel data from the immediate, deferred, and delayed comparisons are presented.

A repeated measures analysis of variance (ANOVA) conducted on all the generalization gradients derived from the A comparisons showed significant effects of testing condition (immediate, deferred, or delayed), $F(2, 24) = 8.81$, $p < .001$, and comparison/standard ratio, $F(6, 72) = 5.68$, $p < .001$. There was also a significant two-way interaction between comparison/standard ratio and testing condition, $F(12, 144) = 10.16$, $p < .001$.

Comparison of performance from the immediate testing of A and deferred testing of A showed a significant effect of comparison/standard ratio, $F(6, 72) = 9.44$, $p < .001$, but no significant effect of testing condition (immediate or deferred) and $F(1, 12) = 0.33$, $p = .58$. There was, however, a significant two-way interaction between comparison/standard ratio and testing condition, $F(6, 72) = 2.52$, $p < .05$.

Comparison of performance from the immediate and delayed testing conditions showed significant effects of testing condition (immediate or delayed), $F(1, 12) = 19.99$, $p < .001$, and comparison/standard ratio, $F(6, 72) = 7.60$, $p < .001$. There was also a significant two-way interaction between comparison/standard ratio and testing condition, $F(6, 72) = 14.56$, $p < .001$.

Comparison of performance from the deferred and delayed testing conditions showed significant effects of testing condition (deferred or delayed), $F(1, 12) = 7.65$, $p < .05$, and comparison/standard ratio, $F(6, 72) = 3.51$, $p < .001$. There was also a significant two-way interaction between comparison/standard ratio and testing condition, $F(6, 72) = 10.35$, $p < .001$.

Discussion

The results of Experiment 1 replicated those of Ogden et al. (2008). When two standards of different durations were encoded and maintained over a delay, there appeared to be a systematic distortion to the memory representation of A in reference memory. In delayed retesting peak responding shifted from at or around the standard to the .75 comparison value. This confirms the suggestion of Ogden et al. that reference

memory has a limited capacity for auditory information and appears unable to accurately maintain multiple different auditory durations over a period of delay.

EXPERIMENT 2

Having replicated the systematic interference effects observed in Ogden et al. (2008) using auditory stimuli, we sought to establish whether the same systematic interference effect would manifest itself in a visual-visual paradigm. Experiment 2 therefore aimed to examine the effects of encoding more than one visual standard in reference memory. The procedure was essentially a replication of that used in Experiment 4a of Ogden et al. (2008), in which participants were presented and tested on the first standard (A) and then presented and tested on the second standard (B). B could be either the same duration as A, or longer than A. Finally participants' memory of A was retested after a delay of 0, 5, 10, 20, or 30 s. All standards and comparisons were blue squares on white backgrounds rather than tones. As in Experiment 1 the focus of interest was in potential differences between performance in immediate, deferred, and delayed testing of A.

Method

Participants

A total of 28 University of Manchester students were paid £5 for participating and were randomly allocated to one of two testing conditions (A = B, *same*; or A < B, *B longer*). Payment was not contingent on performance.

Apparatus

An IBM-PC compatible computer recorded all experimental events. The stimuli were presented on the computer screen in the form of a 4.5×4.5 -cm blue square on a white background. The keyboard collected the participants' responses. E-prime (Psychology Software Tools Inc., Pittsburgh, PA) ran the experiment and recorded all experimental events.

Procedure

The variant of temporal generalization developed in Ogden et al. (2008) was used, and the procedure is essentially a replication of their Experiment 4a. However, instead of presenting auditory stimuli, visual stimuli were used. All stimuli were presented in one experimental session lasting approximately 45 min. Participants were instructed that they would be presented with a standard duration, in the form of a blue square, and that they had to compare the standard with eight comparison durations, stating whether each comparison was the same duration as the standard or different (YES/NO response).

At the beginning of each block participants were presented with the standard duration three times. The duration of the standard was selected randomly from a uniform distribution ranging from 400 to 600 ms, but all three presentations had the same duration value. A delay drawn from a uniform distribution ranging from 1,500–2,000 ms occurred between each presentation of the standard. Participants were then presented with eight comparison durations. The comparison durations were Standard A multiplied by 0.25, 0.50, 0.75, 1.00, 1.00, 1.125, 1.50, 1.75,¹ and they were presented in a random order (A comparisons). After each of the A comparisons, participants had to indicate whether the comparison had the same duration as Standard A by pressing “Y” for YES and “N” for NO on the keyboard. This is subsequently referred to as *immediate testing*. Following the final response to the A comparisons participants were presented with a standard, B, three times. In the *same* condition Standard B was the same length as Standard A, and in the *B longer* condition, Standard B was 400 ms longer than Standard A, whatever A had been in the block. After the presentation of Standard B eight comparison durations were presented (B comparisons). The B comparisons were Standard B multiplied by 0.25, 0.50, 0.75, 1.00, 1.00, 1.125, 1.50, 1.75, and they were

presented in a random order. After each of the B comparisons participants had to indicate whether they were the same length as Standard B by pressing “Y” for YES and “N” for NO on the keyboard. Finally, the A comparisons were presented again after a delay of either 0 (*deferred testing*), or 5, 10, 20, or 30 s (*delayed testing*). Standard A was not re-presented. Participants were instructed to compare the A comparisons to their memory of Standard A. The above procedure was repeated 15 times, with a different duration for Standard A each time. No performance-related feedback was given.

Results

Figure 3 shows temporal generalization gradients from Experiment 2 in the usual form of the mean proportion of YES responses plotted against the comparison/standard ratio for each condition. The upper panel contains data from the *same* condition, the lower panel from the *B longer* condition. Examination of the upper and lower panels suggests that no systematic change in performance occurred from immediate testing to any of the delayed retests. Peak responding remained at or around the standard in all testing conditions. These suggestions were supported by statistical analysis.

An overall ANOVA conducted on all the generalization gradients derived from the A comparisons found no significant effect of group (*same* or *longer*), $F(1, 25) = 0.898$, $p = .352$, nor testing condition (deferred, or 5, 10, 20, or 30 s delay), $F(5, 125) = 0.471$, $p = .797$. However, there was a significant effect of comparison/standard ratio, $F(6, 150) = 44.161$, $p < .001$. There were no significant two- or three-way interactions.

Discussion

The results of Experiment 2 suggest that encoding two visual standards does not lead to a significant

¹ The comparison/standard ratio was changed from that used in Experiment 1 and Ogden et al. (2008). A pilot experiment was conducted using the same comparison standard ratio as that in Experiment 1; however, the task turned out to be too difficult, producing temporal generalization gradients that were almost flat. It was therefore decided to make the task easier by increasing the spacing of the comparison durations around the standard.

Figure 3. Temporal generalization gradients (proportion of YES responses—identifications of a comparison duration as the standard—plotted against comparison/standard ratio) from Experiment 2. Within each panel data from the immediate, deferred, and delayed comparisons are presented. Upper panel: same testing condition; lower panel: B longer testing condition.

deterioration in performance, or any systematic shift in the location of peak responding. The results of the experiment contrast markedly with those using the same method but with auditory stimuli. When A and B were different durations and were presented in the form of auditory stimuli, large systematic shifts in peak responding occurred after a delay prior to retesting (Ogden et al., 2008, and the present Experiment 1). This absence of similar (or indeed any) shift in peak responding when A and B were visual stimuli of different durations supports the view that there are differences in the way auditory and visual durations are stored or maintained in temporal

reference memory. If auditory and visual stimuli were stored in the same way in reference memory the same effects of encoding multiple standards would be expected. The absence of systematic interference using visual stimuli seems to indicate that visually based memories for time intervals may be more robust than those based on auditory stimuli.

EXPERIMENT 3

Experiment 2 demonstrated that multiple visual durations do not interfere with each other in the same way as multiple auditory stimuli, suggesting that visually presented intervals are stored in reference memory in a different way to auditory stimuli. Despite not interfering with each other, it is still possible that visual stimuli may interfere with the memory of auditory stimuli. Experiment 3 investigated whether time intervals derived from stimuli in different modalities interfere with each other in reference memory. The procedure was a modification of that used in Experiment 2; however, Standard A was always auditory, and Standard B was always visual. Standard A was 400 ms shorter, 400 ms longer, or the same duration as B.

The idea that intervals encoded in different modalities may interfere with each other has previously been suggested in memory-mixing accounts of subjective differences in the perception of auditory and visual durations. Memory mixing suggests that auditory and visual memories of a standard may “mix” together in reference memory during timing tasks (Penney et al., 2000). However, Wearden et al. (2006) reported instances in which memory mixing was not possible (as only one modality was experienced by the participant) but modality differences still occurred. Wearden et al. (2006) did not argue that the memory-mixing model was necessarily incorrect, only that it was incomplete: In other words memory mixing may be a sufficient condition for auditory/visual differences but not a necessary one. It is therefore reasonable to expect that the auditory and visual standards in the present task

may interfere with each other. The memory-mixing model might also predict that the peak of temporal generalization responding would occur at a duration somewhere in between the values of A and B, if their memories were mixed. An alternative possibility is that a shift in decision strategy may occur (as seen in Ogden et al., 2008) in which there is a contrast between the memories of A and B resulting in responding at durations much shorter or longer than A, depending on the relation between A and B. If A is longer than B then more responding will occur at durations longer than A, rather than at the duration of A because it is remembered as being longer than it actually was. If A is shorter than B then more responding will occur at durations shorter than A than at the actual duration of A; however, when A and B are the same duration responding remains at the standard as A and B are recalled as being of similar duration.

Whilst all three testing groups (*same*, *B longer*, *B shorter*) were used to examine the effect of differences in the durations of intervals on interference, the *same* condition also allows for examination of the effects of subjective differences in duration. Previous research suggests that for systematic inference to occur A and B must be of different durations. However, the current experiment may expect to find a shift in the location of peak responding when A is auditory, and B is visual, due to subjective differences in the durations of the two stimuli. Auditory stimuli are perceived as lasting longer than visual stimuli (Goldstone & Lhamon, 1974), therefore peak responding might be expected to shift to the right when A is auditory, and B is visual because A will be perceived as being subjectively longer than B. The absence of shift in peak responding would indicate that subjective differences in duration are not sufficient to produce interference like that found with actual differences in duration.

Method

Participants

A total of 45 University of Manchester undergraduate students participated for course credit

and were randomly allocated to one of three groups (*B longer*, *same*, *B shorter*).

Apparatus

The apparatus was the same as that in Experiment 2.

Procedure

The procedure was essentially a replication of Experiment 2 of this article and Experiment 3 of Ogden et al. (2008). The main difference in the current experiment was that the first standard was auditory, and the second standard was visual. The first standard (A) and its comparisons were 500-Hz tones, whereas the second standard (B) and its comparisons were blue squares, 4.5×4.5 cm in size, presented on a white background. The duration of Standard A was randomly selected from a uniform distribution ranging from 800–1,200 ms. Depending on the testing condition, B was 400 ms shorter, 400 ms longer, or the same duration as A. All comparisons were the standard multiplied by 0.625, 0.750, 0.875, 1.00, 1.00, 1.125, 1.250, and 1.375. A delay of 0, 5, 10, 20, or 30 s was imposed before the retesting of A after the final comparison for B. There were 15 blocks in total, all of which were presented in one experimental session lasting approximately 30 minutes. All other experimental details not mentioned explicitly were as Experiment 2.

Results

The data from two participants were excluded due to their displaying extremely poor temporal discrimination.

Figure 4 shows temporal generalization gradients of the mean proportion of YES responses plotted against the comparison/standard ratio for the *same* condition. Comparison of the upper (*same*), middle (*B shorter*), and lower (*B longer*) panels suggests that peak responding remained at or around the standard in all testing conditions. Within each panel there appears to be no significant deterioration in performance from immediate testing to any of the delayed retests. These suggestions were supported by statistical analysis.

Figure 4. Temporal generalization gradients from Experiment 3. Each panel shows data from the immediate, deferred, and delayed comparisons. Upper panel: same testing condition comparisons; centre panel: *B shorter* testing condition comparisons; lower panel: *B longer* testing condition comparisons.

An overall ANOVA conducted on all of the testing groups (*B shorter*, *B longer*, *same*) found significant effects of comparison/standard ratio, $F(6, 240) = 75.31$, $p < .001$, and testing condition,

$F(5, 230) = 2.53$, $p < .05$. There was no significant effect of group, $F(2, 40) = 0.36$, $p = .702$. There were also no significant interactions between testing condition and group, $F(10, 200) = 0.92$, $p = .512$, comparison/standard ratio and group, $F(12, 240) = 0.91$, $p = .54$, or testing condition and comparison/standard ratio, $F(30, 1200) = 0.66$, $p = .92$. The three-way interaction between testing condition, comparison/standard ratio, and group was also not significant, $F(60, 1200) = 1.26$, $p = .09$.

Individual ANOVAs were also conducted for each group using testing condition and comparison/standard ratio as within-subject factors. In the *same* condition there was a significant effect of comparison/standard ratio, $F(6, 102) = 32.48$, $p < .01$. There was no significant effect of testing condition, $F(5, 85) = 1.85$, $p = .11$. There was also no significant interaction between testing condition and comparison/standard ratio, $F(30, 510) = 0.93$, $p = .58$.

In the *B shorter* condition there was a significant effect of comparison/standard ratio, $F(6, 72) = 30.556$, $p < .01$. There was no significant effect of testing condition, $F(5, 60) = 1.04$, $p = .41$, and no significant interaction between testing condition and comparison/standard ratio, $F(30, 360) = 1.23$, $p = .20$.

In the *B longer* condition there was a significant effect of comparison/standard ratio, $F(6, 66) = 17.51$, $p < .01$. There was no significant effect of testing condition, $F(5, 55) = 1.57$, $p = .19$. There was also no significant interaction between testing condition and comparison/standard ratio, $F(30, 330) = 1.07$, $p = .37$.

Discussion

The results of Experiment 3 indicate that encoding multiple standards of different modalities and durations does not result in systematic interference in temporal generalization performance, unlike that observed with auditory stimuli (Ogden et al., 2008). The absence of any significant flattening of temporal generalization gradients, or a shift in the location of peak responding after encoding B and experiencing a delay before

retesting, suggests that auditory and visual stimuli are stored distinctly in reference memory. The absence of any shift in peak responding in the *same* condition also suggests that a subjective difference in the duration of two stimuli was not sufficient to result in systematic interference in performance.

EXPERIMENT 4

Experiment 3 demonstrated that encoding and using a visual standard whilst maintaining an auditory standard in reference memory does not result in systematic interference with the memory of the auditory standard. However, comparison of the results of Experiments 1 and 2 and those of Ogden et al. (2008) suggests that visual standards may be easier to encode and maintain in reference memory, as they do not appear to interfere with each other in the same way as multiple auditory standards. If it is the case that auditory standards are more difficult to encode and maintain than visual standards when memory load is already high (i.e., after encoding A) then encoding an auditory standard after a visual standard may result in systematic interference similar to that seen when two auditory standards are encoded.

Experiment 4 examined the possibility that auditory stimuli are more difficult to process and maintain when memory load is already high. The modified temporal generalization method from Experiments 2 and 3 was used but in Experiment 4 Standard A was visual and Standard B auditory, essentially the reverse of Experiment 3 where A was auditory, and B was visual. Systematic interference when A is visual, and B is auditory would indicate that reference memory is not capable of maintaining an item (of any modality) in reference memory whilst simultaneously encoding and using another auditory item. However, the absence of systematic interference would support the results of Experiments 2 and 3, suggesting that there are fundamental differences in the way that auditory and visual temporal information are encoded and maintained in reference memory.

Method

Participants

A total of 11 Manchester University second-year Psychology undergraduates participated for course credit.

Apparatus

The apparatus was the same as that in Experiments 2 and 3.

Procedure

Experiment 4 was essentially a replication of Experiment 3, except that Standard A was always visual in the form of a blue square (4.5×4.5 cm), and Standard B was always auditory in the form of a 500-Hz tone. The comparison/standard ratio for A was 0.25, 0.50, 0.75, 1.00, 1.00, 1.25, 1.50, 1.75, and the comparison/standard ratio for Standard B was 0.625, 0.75, 0.875, 1.00, 1.125, 1.25, 1.375. Standard B was always 400 ms longer than Standard A. Different comparison/standard ratios were used for the two modalities because Ogden et al. (2008) only found systematic interference when task difficulty was high (comparison/standard ratio of 0.625, 0.75, 0.875, 1.00, 1.00, 1.125, 1.25, 1.375); however, when using visual stimuli more difficult comparison/standard ratios can result in very poor performance. A more difficult set of comparison/standard ratios was used for the auditory comparisons to ensure that the task was difficult enough to induce interference.

The duration of Standard A was drawn from a uniform distribution ranging from 800–1,200 ms. A delay drawn from a uniform distribution ranging from 1,500–2,000 ms was imposed between the presentations of each standard. A delay of 0, 5, 10, 20, or 30 s was imposed after the B comparisons, prior to the re-presentation of the A comparisons. A total of 15 blocks were presented.

Results

Figure 5 shows temporal generalization gradients in the form of the mean proportion of YES responses

Figure 5. Temporal generalization gradients from Experiment 4. The panel shows data from the immediate, deferred, and delayed comparisons.

plotted against the comparison/standard ratio. In all testing conditions peak responding remained at or around the standard. There appeared to be no significant deterioration in performance from immediate testing to after encoding B, or as delay prior to retesting increased. These suggestions were supported by statistical analysis.

A repeated measures ANOVA used testing condition (length of delay) and comparison/standard ratio as within-subjects factors. There was a significant effect of comparison/standard ratio, $F(6, 78) = 41.80$, $p < .001$, but no significant effect of testing condition, $F(5, 65) = 1.03$, $p = .408$, nor was there a significant comparison/standard ratio by testing condition interaction, $F(30, 390) = 1.09$, $p = .344$.

Discussion

Experiment 4 demonstrated that encoding and using an auditory standard whilst maintaining a visual standard in reference memory does not result in significant or systematic interference to the memory of the visual stimuli. The results also suggest that auditory stimuli are not more difficult to process than visual ones when reference memory is already loaded (with either an auditory or a visual stimulus). This therefore suggests that the systematic interference effects observed in

Ogden et al. (2008) were not a result of an increased difficulty in processing auditory stimuli when reference memory is already loaded. Taken together the results of Experiments 3 and 4 suggest that auditory and visual stimuli do not interfere with each other in reference memory when the second standard encoded is of a different modality and duration to the first.

GENERAL DISCUSSION

Comparison of the results presented in this article with those in Ogden et al. (2008) suggests that there are fundamental differences in the way that the durations of auditory and visual stimuli are encoded and stored in reference memory, and in the stability of that storage. When multiple auditory stimuli of different durations are encoded, reference memory appears incapable of maintaining the first stimulus after processing the second, when a period of delay is imposed prior to retesting. This is reflected in the systematic interference characterized by shifts in the location of peak responding after the delay. In contrast, when multiple visual stimuli of different durations are encoded and maintained over a period of delay (Experiment 2) no systematic interference occurred. The absence of systematic interference suggests that reference memory is capable of accurately storing the durations of multiple visual stimuli over a delay. The storage of visual temporal information therefore appears to be more permanent and less vulnerable to interference than is that of auditory stimuli.

When examining potential interference between duration representations from stimuli of different modalities, Experiments 3 and 4 demonstrated that items in reference memory of different modalities do not appear to interfere with each other. When A was auditory, and B was visual (or vice versa) peak responding remained at or around the standard after even a 30 s delay and in conditions where A and B were different durations. The absence of any systematic interference or general deterioration in performance in these experiments indicates that it is only multiple

auditory stimuli that reference memory is incapable of maintaining separately, rather than an inability to encode and maintain auditory stimuli when reference memory is loaded with any other stimuli. This suggests the possibility that temporal memory is superior for visual stimuli.

A superior memory for visual stimuli over auditory stimuli is surprising as previous research within and outside the temporal domain suggests that the processing and storage of auditory stimuli is superior to that of visual stimuli. Rhythm memory has been found to be superior when auditory rather than visual stimuli are used (Glenberg & Jona, 1991), and the timing of auditory stimuli is consistently found to be more accurate than that of visual stimuli (Wearden et al., 1998). Auditory stimuli are also more readily processed than visual stimuli (Jaskowski, Jaroszyk, & Hojan-Jazierska, 1990), and when auditory and visual stimuli are presented simultaneously the auditory stimuli appear to contribute more to the timing judgement than the visual one (Penney et al., 2000), the phenomenon of “auditory dominance” (e.g., Walker & Scott, 1981). In fact, the greater ease of timing auditory than visual stimuli was remarked on as early as 1868 by Vierordt (see Lejeune & Wearden, 2009).

At first sight the findings reported in the present article appear to be inconsistent with previous literature that has found comparable performance on auditory and visual tasks when reference memory function is known to be altered by age (Droit-Volet et al., 2001; McCormack et al., 1999), drug intake (Meck, 1983, 1987; Meck & Church, 1987a, 1987b) or brain damage (Meck et al., 1987; Olton, 1989). The results, however, are still compatible with the idea of a single reference memory for all durations if we consider the idea of reference memory being a pool, which has different areas within it. So, for example, there may be one general reference memory that holds all temporal information required for long-term storage. Within this general store there may be different areas for different modalities—for example, auditory and visual. Within these different areas manipulations may have different effects depending upon modality. Under this assumption

it is therefore possible to account for why some manipulations, such as changes in age and intake of drug, would affect all modalities equally as they exert a “global” effect on reference memory. In addition it is also possible to accommodate different effects on different modalities—for example, the presence of systematic interference when encoding multiple auditory stimuli but not visual stimuli. The idea of separate storage areas for different modalities is also compatible with the finding that auditory and visual stimuli did not appear to interfere with each other as they are stored in distinct areas.

In conclusion, whilst the idea of reference memory being a series of distinct areas subserved by the same global system can accommodate the findings of this article and those of Ogden et al. (2008), it remains unclear why the visual component of this system would be more resistant to interference than the auditory component. The superiority for the storage of visual durations in reference memory also suggests that storage itself may not be the cause of the more general finding in the literature of more variable performance in visual tasks than in auditory ones. It may instead be the case, however, that transformation from working memory to reference memory, or the perceptual process itself, results in more variable visual temporal performance. This issue could be clarified by manipulating the circumstances under which encoding takes place—for example, providing more or less opportunity for encoding, or examining auditory/visual performance differences on tasks that did not require the use of reference memory (e.g., the “episodic” generalization procedure of Wearden & Bray, 2001).

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REFERENCES

- Behar, I., & Bevan, W. (1961). The perceived duration of auditory and visual intervals: Cross-modal comparison and interaction. *American Journal of Psychology*, 74, 17–26.

- Brown, S. W. (1997). Attentional resources in timing: Interference effects in concurrent temporal and non-temporal working memory tasks. *Perception and Psychophysics*, 59, 1118–1140.
- Brown, S. W. (1998). Automaticity versus timesharing in timing and tracking dual-task performance. *Psychological Research*, 61, 71–81.
- Brown, S. W., Stubbs, D. A., & West, A. N. (1992). Attention, multiple timing, and psychophysical scaling of temporal judgements. In F. Macar, V. Pouthas, & W. J. Friedman (Eds.), *Time, action and cognition* (pp. 129–140). Dordrecht, The Netherlands: Kluwer Academic Publishers.
- Brown, S. W., & West, A. N. (1990). Multiple timing and the allocation of attention. *Acta Psychologica*, 75, 103–121.
- Church, R. M. (1984). The properties of the internal clock. *Annals of the New York Academy of Sciences*, 423, 566–582.
- Church, R. M., & Gibbon, J. (1982). Temporal generalization. *Journal of Experimental Psychology: Animal Behavior Processes*, 8, 165–186.
- Droit-Volet, S. (2002). Scalar timing in temporal generalization in children with short and long stimulus durations. *Quarterly Journal of Experimental Psychology*, 55A, 1193–1209.
- Droit-Volet, S., Clément, A., & Wearden, J. H. (2001). Temporal generalization in 3- to 8-year-old children. *Journal of Experimental Child Psychology*, 80, 271–288.
- Droit-Volet, S., & Wearden, J. H. (2001). Temporal bisection in children. *Journal of Experimental Child Psychology*, 80, 142–159.
- Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences*, 423, 52–77.
- Glenberg, A. M., & Jona, M. (1991). Temporal coding in rhythm tasks revealed by modality effects. *Memory and Cognition*, 5, 514–522.
- Goldstone, S., Boardman, W. K., & Lhamon, W. T. (1959). Intersensory comparisons of temporal judgements. *Journal of Experimental Psychology*, 57, 243–248.
- Goldstone, S., & Lhamon, W. T. (1974). Studies of auditory-visual differences in human time judgement: 1. Sounds are judged longer than lights. *Perceptual and Motor Skills*, 39, 63–82.
- Grondin, S. (2005). Overloading temporal memory. *Journal of Experimental Psychology: Human Perception and Performance*, 31, 869–879.
- Grondin, S., & Rousseau, R. (1991). Judging the relative duration of multimodal short empty time intervals. *Perception & Psychophysics*, 49, 245–256.
- Jaskowski, P., Jaroszyk, F., & Hojan-Jeziarska, D. (1990). Temporal-order judgments and reaction time for stimuli of different modalities. *Psychological Research*, 52, 35–38.
- Jones, L. A., & Wearden, J. H. (2004). Double standards: Memory loading in temporal reference memory. *Quarterly Journal of Experimental Psychology*, 57B, 55–77.
- Lejeune, H., & Wearden, J. H. (2009). Vierordt's "The Experimental Study of the Time Sense" (1868) and its legacy. *European Journal of Cognitive Psychology*.
- McCormack, T., Brown, G. D. A., Maylor, E. A., Darby, R. J., & Green, D. (1999). Developmental changes in time estimation: Comparing childhood and old age. *Developmental Psychology*, 35, 1143–1155.
- McCormack, T., Brown, G. D. A., Maylor, E. A., Richardson, L. B., & Darby, R. J. (2002). Effects of aging on absolute identification of duration. *Psychology and Aging*, 17, 363–378.
- Meck, W. H. (1983). Selective adjustment of the speed of internal clock and memory processes. *Journal of Experimental Psychology: Animal Behavior Processes*, 9, 171–201.
- Meck, W. H. (1987). Vasopressin metabolite neuropeptide facilitates simultaneous temporal processing. *Behavioural Brain Research*, 23, 147–157.
- Meck, W. H., & Church, R. M. (1987a). Cholinergic modulation of the content of temporal memory. *Behavioural Neuroscience*, 101, 457–464.
- Meck, W. H., & Church, R. M. (1987b). Nutrients that modify the speed of internal clock and memory storage processes. *Behavioural Neuroscience*, 101, 465–475.
- Meck, W. H., Church, R. M., & Wenk, G. L. (1986). Arginine vasopressin inoculates against age-related increases in sodium-dependent high affinity choline uptake and discrepancies in the content of temporal memory. *European Journal of Pharmacology*, 130, 327–331.
- Meck, W. H., Church, R. M., Wenk, G. L., & Olton, D. S. (1987). Nucleus basalis magnocellularis and medial septal area lesions differentially impair temporal memory. *Journal of Neuroscience*, 7, 3505–3511.
- Meck, W. H., & Williams, C. (1997). Characterization of the facilitative effects of prenatal choline supplementation on timing and temporal memory. *Learning and Memory*, 8, 2831–2835.
- Ogden, R. S., Wearden, J. H., & Jones, L. A. (2008). The remembrance of times past: Interference in temporal

- reference memory. *Journal of Experimental Psychology: Human Perception and Performance*, 34, 1524–1544.
- Olton, D. S. (1989). Frontal cortex, timing and memory. *Neuropsychologia*, 27, 121–130.
- Penney, T. B., Gibbon, J., & Meck, W. H. (2000). Differential effects of auditory and visual signals on clock speed and temporal memory. *Journal of Experimental Psychology: Human Perception and Performance*, 26, 1770–1787.
- Walker, J. T., & Scott, K. J. (1981). Auditory-visual conflicts in the perceived duration of lights, tones and gaps. *Journal of Experimental Psychology: Human Perception and Performance*, 7, 1327–1339.
- Wearden, J. H., & Bray, S. (2001). Scalar timing without reference memory: Episodic temporal generalization and bisection in humans. *Quarterly Journal of Experimental Psychology*, 54B, 289–310.
- Wearden, J. H., Edwards, H., Fakhri, M., & Percival, A. (1998). Why “sounds are judged longer than lights”: Application of a model of the internal clock in humans. *Quarterly Journal of Experimental Psychology*, 51B, 97–120.
- Wearden, J. H., Todd, N. P. M., & Jones, L. A. (2006). When do auditory/visual differences in duration judgements occur? *Quarterly Journal of Experimental Psychology*, 59, 1709–1724.
- Wearden, J. H., Wearden, A. J., & Rabbitt, P. M. A. (1997). Age and IQ effects on stimulus and response timing. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 962–979.