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Good vibrations: Human interval timing in the vibrotactile modality

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This article reports a detailed examination of timing in the vibrotactile modality and comparison with that of visual and auditory modalities. Three experiments investigated human timing in the vibrotactile modality. In Experiment 1, a staircase threshold procedure with a standard duration of 1,000 ms revealed a difference threshold of 160.35 ms for vibrotactile stimuli, which was significantly higher than that for auditory stimuli (103.25 ms) but not significantly lower than that obtained for visual stimuli (196.76 ms). In Experiment 2, verbal estimation revealed a significant slope difference between vibrotactile and auditory timing, but not between vibrotactile and visual timing. That is, both vibrations and lights were judged as shorter than sounds, and this comparative difference was greater at longer durations than at shorter ones. In Experiment 3, performance on a temporal generalization task showed characteristics consistent with the predications of scalar expectancy theory (SET: Gibbon, 1977) with both mean accuracy and scalar variance exhibited. The results were modelled using the modified Church and Gibbon model (MCG; derived by Wearden, 1992, from Church & Gibbon 1982). The model was found to give an excellent fit to the data, and the parameter values obtained were compared with those for visual and auditory temporal generalization. The pattern of results suggest that timing in the vibrotactile modality conforms to SET and that the internal clock speed for vibrotactile stimuli is significantly slower than that for auditory stimuli, which is logically consistent with the significant differences in difference threshold that were obtained.

Keywords: Time perception; Difference threshold; Modality differences; Clock speed; Vibrotactile.

Time psychology researchers have traditionally taken an interest in differences and similarities in the timing of the different modalities. This interest was born of two major needs: first to test whether theoretical models and predictions of timing behaviour are generalizable to more than the modality in which they were conceived, and secondly to try and explain the existence of certain well-known differences in the subjective duration of auditory and visual stimuli. Both of these endeavours have almost exclusively focused on the visual and auditory systems with the

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tactile system largely ignored. Partly this has been due to methodological difficulties in controlling tactile stimuli,[1] but it is also due to the fact that it is only more recently that we have had a theoretical framework that allows us to try and explain modality differences rather than just describe them.

Between-modality comparisons of temporal sensitivity

Some previous work on temporal sensitivity in the different modalities has been reported over the last century, using a variety of different techniques. However, the majority of previous work has focused on modality differences between vision and audition and finds superior temporal sensitivity in the auditory modality. For example, Exner (1895) found that flashes of light were considered successive rather than simultaneous when separated by 44 ms, whilst auditory stimuli only needed be separated by as little as 2 ms (also see Hirsh & Sherrick, 1961). Grondin, Meilleur-Wells, Ouellette, and Macar (1998) using a forced-choice adaptive procedure (similar to that used in Experiment 3 of our study) found a lower difference threshold for audition than for vision for the discrimination of both filled and unfilled intervals.

Far less prominent in the literature are studies incorporating the tactile modality, or a comparison of all three modalities. One such study (although only using touch and audition) comes from Gridley (1932). Using a paired comparison method, participants were required to judge whether a second presented duration was longer or shorter than the first. Gridley found better discrimination for hearing than for touch in terms of number of correct judgements. Actual thresholds are hard to infer from the methodology used as a full range of stimulus differences were not used but examination of the figures suggest between 90 and 140 ms for both modalities (at 75% correct level) for a 1,000-ms standard. Goodfellow (1934) used three separate techniques to determine the temporal sensitivity of audition, vision, and touch, using the aforementioned Gridley as the one and only "expert subject" who conducted over 1,400 trials. Goodfellow concluded that "all three techniques show audition to have the keenest differential sensitivity and vision the poorest, with touch lying midway between audition and vision" (p. 256). Slightly different thresholds were obtained depending on the technique used. For a paired comparison (similar to that used by Gridley, 1932), values of 70 ms for audition, 100 ms for touch, and 137 ms for vision were obtained whereas for a type of just noticeable difference (JND) task, values of 59 ms (audition), 94 ms (touch), and 118 ms (vision) were obtained; a 1,000-ms standard was used in all tasks.

In a relatively recent study, Buffardi (1971) also used all three sensory modalities and found that discrimination for auditory stimuli was better than that for tactile stimuli, which in turn was better than that for visual stimuli, consistent with the pattern of the results of Gridley and Goodfellow. However the experiments by Buffardi were conducted for other reasons (to investigate the filled-duration illusion: see Goldstone & Goldfarb, 1963; also Wearden, Norton, Martin, & Montford-Bebb, 2007, for a modern review and theoretical exploration), and as such only relative and not quantifiable thresholds are given.

Another recent study comparing temporal performance in the three modalities is that of Westheimer (1999). Participants were presented with two durations, and they simply had to report whether the test interval was longer or shorter than the comparison interval. It was found that the Weber fraction was smaller for auditory stimuli than for visual or tactile stimuli. Westheimer (1999) only presents data from 2 participants in his results (1 of which is Westheimer

[1] For an example of the kind of difficulties that early experimenters were faced with (and the extraordinary and ingenious lengths to which they went to overcome them), we recommend that the reader examine the work of Gridley (1932).

himself), and these appear to uphold the auditory superiority over vision, but his 2 participants G.W. and B.H. place touch differently; G.W. places it between vision and audition (Weber fraction of 4.8% for vision, 4.0% for hearing, and 4.2% for touch), while B.H. places it as less sensitive than vision (5.9 % for vision, 3.9% for hearing, 7.2% for touch). It should be noted that the nature of the tactile stimuli was different for G.W. (both the start and the end of the interval were marked by a 3-ms upward displacement of the button on which the finger rested) and B.W. (sequence of 5-ms pulses lasting for the duration of the interval).

It should be noted that work examining different modalities in respect of temporal order judgements does exist (e.g., Miyazaki, Yamamoto, Uchida, & Kitazawa, 2006; Spence, Shore, & Klein, 2001) but this work is not directly relevant when considering actual timing sensitivity.

Our Experiment 1 was conducted to address the issue of calculating difference thresholds for all three modalities using a modern experimental methodology, equipment, and stimulus control with a large nonexpert participant group. Based on the previous literature we might expect the lowest threshold for audition and the highest for vision, with touch lying somewhere between the two.

Between-modality comparisons of clock speed

One of the most pervasive effects noted in the timing literature is the observation that "sounds are judged longer than lights" (Goldstone & Lhamon, 1974). An auditory stimulus is judged as longer than a visual stimulus of the same physical duration, an effect that some authors date back to Goldstone, Boardman, and Lhamon (1959), but others date back to the 19th century (Fraisse, 1964, traces it back to Meumann, 1896). Goldstone et al. (1959) showed that participants judged longer visual than auditory durations as being equal to one second. These results were supported by Behar and Bevan (1961) and have since been supported by others using various methods (Goldstone & Lhamon, 1972, 1974), including direct comparison rather than absolute judgements as used in Goldstone et al. (1959) (Goldstone & Goldfarb, 1964) and production and reproduction (Goldstone, 1968).

More recently this effect has been explored within the context of internal-clock theory, specifically scalar expectancy theory (SET; Gibbon, 1977) by Wearden, Edwards, Fakhri, and Percival (1998). Wearden et al. ascribe this difference in the perceived duration of auditory and visual stimuli to a difference in the speed of a supposed internal clock. The signatures of such clock speed effects are slope effects. For example, Wearden et al. (1998) used a verbal estimation task; participants were given a number of tones of different duration and were asked to verbally label their duration, followed by the same task with visual stimuli. When real and estimated durations were plotted against each other the slope of the two functions differed, with a steeper slope for auditory stimuli than for visual stimuli. The crucial argument is that this slope effect is indicative of some multiplicative process (theoretically assigned to a speeding up of an internal clock/pacemaker) and not a simple over/underestimation bias or switch latency/lag (between an internal pacemaker and some accumulator), which would manifest itself as an intercept effect.

Wearden et al. (1998) attributed the auditory/visual differences in duration judgements to differences in the speed of the pacemaker of the internal clock, with the pacemaker running faster for auditory stimuli than for visual stimuli, resulting in the slope effects observed. An objection has been raised to this simple clock speed explanation by Penney, Gibbon, and Meck (2000). They suggested that an additional effect of memory mixing may be the principal agent producing (or magnifying) this effect. Memory mixing suggests that all the presented durations from auditory and visual stimuli delivered in the same experimental session are mixed in reference memory producing an average value, resulting in subsequent auditory stimuli being judged as longer than this composite memory, and visual stimuli being judged as shorter. Penny et al.'s idea predicted that if a participant receives only one modality, then memory mixing cannot occur, and the modality difference, with auditory stimuli being judged as longer, will not occur or will at least be weakened. However, Wearden, Todd, and Jones (2006) have since demonstrated that modality effects (i.e., auditory/visual differences) cannot only be obtained when people receive just one stimulus modality, but that the size of the effect was identical to that when they received both.

To date, while the auditory/visual difference is well documented and has been demonstrated with a variety of methods and participant groups, there has been no research into clock speed effects of this type in the tactile modality. The present research aims to see how the timing of vibrotactile stimuli fits into these modality differences and whether any differences in timing will be observed between vision, touch, and audition. We therefore chose to use a verbal estimation task and to compare the slopes of the produced psychometric functions for the timing of vibrotactile, visual, and auditory stimuli.

Determination of scalar properties in timing

For our Experiment 3 we chose to use a temporal generalization technique (for a full examination, see Wearden, 1992) in order to examine the operation of the timing system when the stimulus modality is vibrotactile. The usefulness of the temporal generalization technique for this purpose is threefold. First it allows for testing of the two key predictions of SET: mean accuracy and a constant coefficient of variation. In order to show mean accuracy, the temporal generalization function should peak at the standard duration. In order to demonstrate a constant coefficient of variation, the task will be conducted twice with two different standard duration values. The generalization functions from these two tasks when plotted on the same relative scale should superimpose upon each other (or at least not deviate significantly).

Secondly, the temporal generalization technique is also useful for eliciting other particular characteristics of timing performance. The most pervasive of these (so far only demonstrated in the visual and auditory modalities) is the asymmetry of temporal generalization gradient (rightward skewed). This asymmetry shows that human participants consistently identify comparison durations that are longer than the standard as the standard more often than those that are shorter. (For a discussion and explanation of this property based on decision rules see Wearden, 1992.) Thirdly a sophisticated mathematical model of how the SET system operates during temporal generalization is available called the modified Church and Gibbon model (Church & Gibbon, 1982), modified for humans by Wearden (1992). This can be used in order to determine parameter values for different parts of the system—that is, reference memory variance, memory distortion, threshold value, and threshold variance. These values can then be compared to those previously reported in the literature for visual and auditory stimuli.

The uniqueness of our approach is that we examined both difference thresholds (Experiment 1) and psychometric functions (Experiment 2) for the same stimuli. Hence we are able to draw more meaningful theoretical conclusions than we are currently able to from the literature outlined to date. Unlike another previous study (Westheimer, 1999) we use nonexpert participants, rather than one participant who performs hundreds or even thousands of trials. An additional problem with previous studies comparing timing between sensory modalities is that the locations of stimuli were not matched, so auditory stimuli may have been presented through headphones and visual stimuli on a screen. Thus, the location as well as the modality of the stimulus differed, which has previously been shown to have an effect on attending to the stimulus (Spence & Driver, 1997). We addressed this issue in our experiments by positioning the apparatus for producing the stimuli (speaker; bone conductor; light-emitting diode, LED) in the same location. Additionally, in Experiment 3, we tested for the first time whether the predictions of SET apply to the timing of tactile stimuli.

EXPERIMENT 1

A key question when examining temporal performance is the determination of difference threshold. We used the weighted up-down staircase method developed by Kaernbach (1991) from the transformed up-down method of Levitt (1971). The task is elegant in its simplicity; a standard value is chosen (e.g., 500 ms), and then on each trial two stimuli are presented—the standard stimulus and the comparison stimulus (standard duration plus some value, e.g., 700 ms)—with the order of the two stimuli varied randomly on each trial. The participant is simply asked which of the two stimuli is the longest in duration; if the participant answers correctly then on the next trial the difference between the two stimuli is reduced, if incorrect then the difference is increased. In this manner the technique "hunts out" their difference threshold. Typically there will be around 50 trials, with the threshold value being determined by the mean difference over the last 20 trials. A change in step size (increases and decreases in standard and comparison difference) is often incorporated—for example, after the first 30 trials the step size is decreased in order to find a more precise value for the participants' difference threshold.

The weighted up-down method allows for convergence at any desired point of a psychometric function by allowing for a different step size for upward steps (Sup) than for downward steps (Sdown; Rammsayer, 1992). The formula for the equilibrium point X_p is

$$S_{up}p = S_{down}(1 - p).$$

In our investigation we decided to use the generally accepted convention of finding the X_{75} of the psychometric function, which is the point at which the participants could correctly distinguish between the two durations with a difference of X 75% of the time. This necessitated decreasing the difference between the two durations by one step size for every correct response on the previous trial and increasing it by three step sizes for every incorrect response. The use of this procedure to determine threshold values in the temporal domain has been popularized by Rammsayer and colleagues. Rammsayer (1992) demonstrated the efficiency of the weighted up-down technique for reaching the equilibrium point of X_p compared to the transformed up-down technique. As well as providing a threshold value for each participant in each modality this technique also allows us to see which modalities significantly differ from each other in their difference threshold values in order to determine their relative sensitivities.

A difference threshold is dependent upon the durations being used (Weber's law). For the sake of standardization we chose to seek the difference threshold for a 1-s duration (1,000 ms); the comparison duration was set at 700 ms in order to be sufficiently easy as to not deter the participant with a seemingly impossible task, but not so easy as to take too many trials to reduce down to the participant's difference threshold.

From previous work, such as that of Gridley (1932) or Goodfellow (1934), we might expect audition to be most sensitive, which would be denoted by a smaller average threshold, and vision to be least sensitive, with the tactile modality falling somewhere in between.

Method

Participants

A total of 28 undergraduate students at the University of Manchester participated for course credit, which was not, however, contingent on performance.

Apparatus

The experiment was conducted in a small cubicle, insulated from external lights and noise. Participants were seated in front of a Dell PC computer; the monitor was used to present instructions, and participants entered their responses into the keyboard with their nondominant hand. The experimental programs were written using the E-Prime system (Psychology Software Tools Inc.). Vibrotactile stimuli were presented through a bone conductor with a vibrating surface 1.6 cm wide and 2.4 cm long (Oticon Limited, B/C 2-PIN, 100 ohm, Hamilton, UK). The bone conductors were mounted into a foam cube, which participants held in their dominant hand, with their index finger pad over the bone conductor. White noise (a random signal of every frequency in the audio spectrum, all of which have an average uniform power level), via an external amplifier, was used to produce the auditory stimuli (via an external speaker) and the vibrotactile stimuli (via the bone conductor). Visual stimuli were produced by a red LED (approximately 4 mm in diameter) mounted in foam. All stimuli were suprathreshold, and the bone conductor, LED, and speaker were placed in the same approximate spatial location.

Procedure

Participants received all three modalities in separate blocks in a counterbalanced order of presentation during an experimental session of around 30 minutes duration. Participants were presented with two durations, beginning at 1,000- and 700-ms duration, respectively. At the instruction of the computer, participants pressed "1" or "2" on the keyboard, depending on whether they judged the first (1) or second (2) stimulus to be longer, after each trial. The step size, by which to increase or decrease the difference between stimulus durations, began at 15 ms, falling to 10 ms after 30 trials. A total of 50 trials were completed in total. In order to mask any noise produced by the delivery of the vibrotactile stimuli, participants listened to continuous white noise presented through headphones during the vibrotactile trials to eliminate this confounding factor. They also listened to the white noise throughout the visual trials.

Results

Due to a computer error the visual data were not recorded for 5 participants. Additionally 2 participants had thresholds more than three standard deviations from the mean (for the visual, auditory, and tactile tasks) and were removed from analysis. Thus the data from 26 participants were analysed with 21 scores for the visual task and 26 scores for each of the tactile and auditory tasks.

Figure 1 shows the mean difference thresholds across all trials for the different modalities. Inspection of Figure 1 suggests that the procedure was successful in focusing in on the difference threshold for each modality, with the function appearing stable and flat over the last 20 trials; the average difference over these trials was used as the threshold measure for each participant. As can be seen, it appears that the discrimination of auditory stimuli has the lowest difference threshold (103.25 ms), discrimination of visual stimuli produced the highest difference threshold (196.76 ms), and the vibrotactile stimuli difference threshold (160.38 ms) falls approximately halfway between auditory and visual thresholds. With regard to the standard deviations, thresholds were most variable for visual stimuli (*SD* 88.61 ms) and least variable for auditory stimuli (*SD* 56.73 ms), with vibrotactile thresholds again falling between the two (*SD* 66.34 ms).

A repeated measures analysis of variance using modality type as the within-subjects factor with three levels (visual, auditory, and tactile) revealed a significant effect of stimulus modality, $F(2, 40) = 11.30$, $p < .001$. Planned paired-sample *t* tests revealed a significant difference between auditory and visual thresholds, $t(20) = 4.37$, $p < .001$, and between auditory and vibrotactile

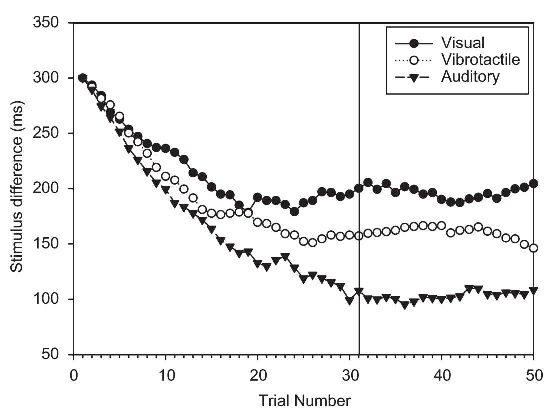

Figure 1. *Mean stimulus difference (standard minus comparison in ms) plotted against trial number for the conditions in Experiment 1.*

thresholds, $t(25) = 4.078$, $p < .001$; the difference between the visual and vibrotactile thresholds failed to reach statistical significance, $t(20) = 1.574$, $p = .13$.

Discussion

These results confirm the dominant finding in the literature that auditory stimuli produce a lower threshold than visual stimuli, showing that the auditory system is more sensitive to discriminations of duration than is the visual system.

Additionally, our results showed that auditory temporal discrimination was significantly better than vibrotactile discrimination, but there was no significant difference between visual and vibrotactile thresholds. Although the difference between visual and vibrotactile thresholds failed to reach statistical significance, there was a reduction in statistical power due to the loss of 5 participants' data. However, the same degree of statistical power did produce a significant difference between the visual and auditory thresholds. Table 1 shows the results in the context of those obtained in the studies previously discussed. Inspection of Table 1 shows that with the exception of 1 participant in one study (participant B.H. in Westheimer, 1999) the same pattern of relative thresholds is evident: auditory thresholds being the lowest, followed by tactile, followed by vision. Examination of the Weber ratios also shows that our obtained values are in broad alignment with those previously found, although a little higher overall.

In conclusion, Experiment 1 demonstrates that duration discrimination is superior with auditory stimuli and least sensitive with visual stimuli, and that vibrotactile thresholds are significantly worse than auditory and lie closer to that of visual thresholds.

EXPERIMENT 2

Further to the well-replicated finding that auditory stimuli are judged to be longer than visual stimuli of the same physical duration, Experiment 2 sought to investigate whether there were similar differences between the judgement of tactile stimuli and that of visual and/or auditory stimuli. It has been suggested that verbal estimation may reflect the "rawest" type of judgement possible (Wearden, 1999) and reflect quite directly the contents of the accumulator/working memory of the scalar timing system. It is for this reason that we chose to use verbal estimation in the comparison of the three modalities in the present study as it is the most direct way

Table 1. *Weber ratios from previous studies of temporal discrimination in different sense modalities including the results from Experiment 1*

			Weber ratio (%)		
Study	*Methodology*	*Standard*	*Hearing*	*Touch*	*Vision*
Gridley (1932)	Paired comparison	1,000 ms	9–14[a]	9–14[a,b]	N/A
Goodfellow (1934)	Paired comparison	1,000 ms	7	10	13.7
	JND-type task		5.9	9.4	11.8
Buffardi (1971)	Paired comparison	1,056 ms	Best[c]	Intermediate	Worst
Grondin et al. (1998)	Forced-choice adaptive procedure	400 ms	3.6–4.9[a]	N/A	6.4–9[a]
	Forced-choice adaptive procedure	800 ms	7.2–8.1	N/A	10–12.1[a]
Westheimer (1999)	Paired comparison: Participant G.W.		4.0	4.2	4.8
	Paired comparison: Participant B.H.		3.9	7.2	5.9
Current study, Experiment 1	Forced-choice adaptive procedure	1,000 ms	10.3	16.0	19.7

Note: JND = just noticeable difference.
[a]Inferred from figures. [b]Higher than for hearing. [c]Actual threshold value not given.

of revealing clock speed differences without having to resort to a more complicated state change paradigm. Verbal estimation simply requires that participants estimate, in milliseconds, the duration of a presented stimulus. Using this method, Wearden et al. (1998) demonstrated that mean estimates for auditory stimuli were significantly higher than those for visual stimuli, and that the difference between them increases as the duration to be estimated increases (a slope effect) and that estimates for visual stimuli were more variable.

We would expect the present experiment to not only replicate the auditory/visual difference found in so many studies (e.g., Behar & Bevan, 1961; Goldstone et al., 1959; Goldstone & Lhamon, 1974; Wearden et al., 1998), but also determine how tactile stimuli fit into this scheme. As no previous work has investigated this effect, it can only be postulated that slopes (and thus inferred clock speeds) for tactile judgements may lie between those of visual and auditory stimuli.

Method

Participants

A total of 22 psychology undergraduate students at the University of Manchester participated for course credit, which was not contingent on performance.

Apparatus

All apparatus was identical to that used in Experiment 1.

Procedure

The stimuli for each modality were identical to those used in Experiment 1. The durations used in this experiment were 77, 203, 348, 461, 582, 767, 834, 958, 1,065, and 1,183 ms. Participants were advised that all stimuli were between 50 and 1,500 ms in duration, and that 1 s was equal to 1,000 ms. In an experimental session lasting approximately 30 minutes, participants received three blocks of stimuli, one for each modality, with the order of presentation counterbalanced across participants. Each block consisted of 40 stimuli, with each duration presented three times in a random order. Participants initiated each stimulus by pressing the spacebar and typed in their estimate in milliseconds following the end of each stimulus. They were then given the instruction "press spacebar for next trial"; upon the pressing of the spacebar the next trial would begin. No feedback regarding the accuracy of the estimates was given. Again, participants listened to white noise from a portable CD player during all vibrotactile trials to block out the noise from the bone conductor, and also during all visual trials.

Results

A total of 3 participants were removed from the subsequent analysis due to a failure to comprehend or comply with instructions. Additionally, before analysis the data were filtered to remove any estimates falling outside the 50- to 1,500-ms range that participants were advised the stimuli fell between, to remove any mistyping — for example, 100 as 10 ms, and so on. The data were analysed in two different ways: initially using verbal estimates, and then using slope and intercept values derived from regression analysis.

Inspection of Figure 2 suggests that mean estimates increased as an approximately linear function of actual stimulus duration in all three conditions. Furthermore estimates of stimulus duration appear to be consistently longer for the auditory stimuli than for both the visual and tactile conditions. There appeared to be little or no difference between the visual and tactile functions.

Verbal estimates

An analysis of variance (ANOVA) of all conditions together using modality (auditory, visual, and tactile) and stimulus length showed a significant effect of modality on estimates, $F(2, 36) = 8.55$, $p < .01$, a significant effect of stimulus length, $F(9, 162) = 269.96$, $p < .001$, and a significant Modality × Stimulus Length interaction, $F(18, 324) = 3.206$, $p < .001$. The Modality × Stimulus Length interaction is suggestive of a slope difference between conditions.

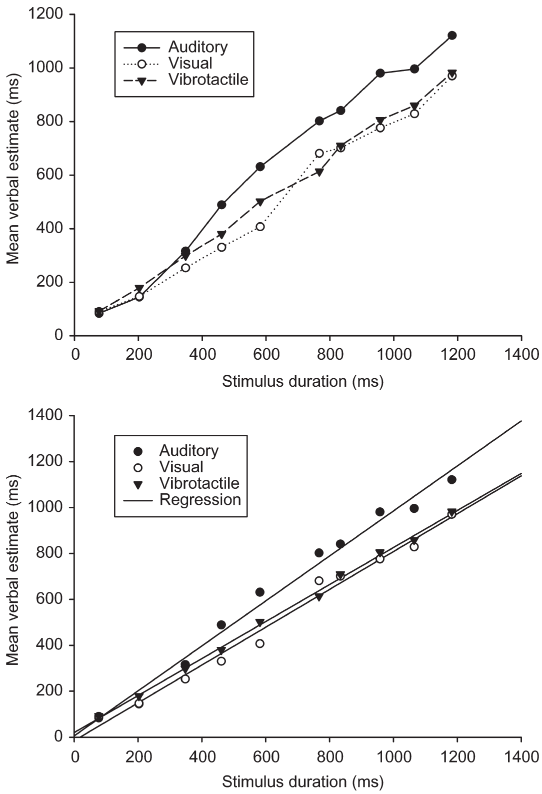

Figure 2. *Mean verbal estimates plotted against stimulus duration (both in ms) for the conditions of Experiment 2. Lines represent linear regressions.*

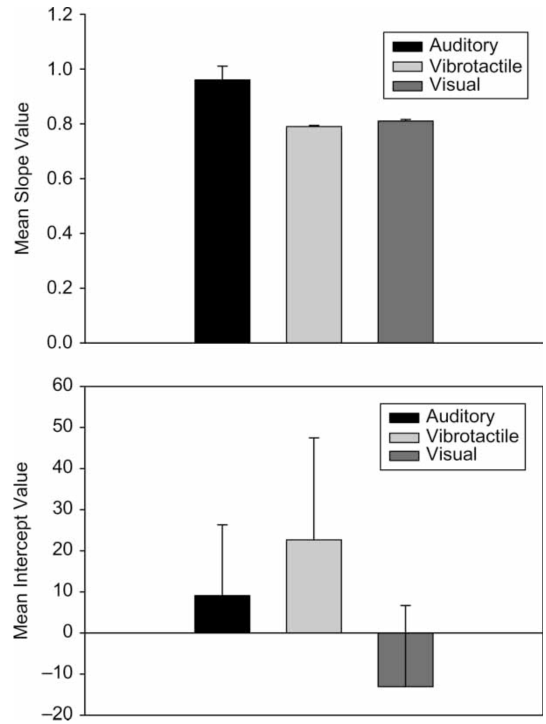

Figure 3. *Mean intercept and slope values derived from regression of individual participant's data from Experiment 2. Upper panel: slope values. Lower panel: intercept values.*

Therefore, based on the overall mean verbal estimates there is a significant overestimation of durations for the auditory stimuli compared to the visual and vibrotactile stimuli. Furthermore this overestimation appears to be dependent upon the duration of the stimuli, indicating more than a simple bias effect. For a more thorough examination of these effects it is necessary to calculate individual linear regressions; we discuss the specific modality effects in relation to this analysis in the next section.

Slope and intercept

Regression of data for each individual participant was performed; the slope and intercept values were calculated for each modality and are shown in Figure 3. Inspection of Figure 3 suggests that the slope of the auditory judgements is significantly higher than that for the visual and tactile judgements, which appear to be very similar. Inspection of the intercept values (lower) suggest that the intercept values were variable and may not differ from each other significantly. These suggestions were supported by the subsequent statistical analyses.

An ANOVA on slope values derived from regression of data from individual participants found a significant effect of modality, $F(2, 36) = 5.64$, $p < .05$. Planned pairwise comparisons found that the auditory slope was significantly higher than the visual slope, $t(18) = 2.29$, $p < .05$, and the tactile slope, $t(18) = 4.18$, $p < .01$, but there was no significant difference between the visual and tactile slopes, $t(18) = 0.32$, $p = .75$. Analysis of intercept values found no effect of modality, $F(2, 36) = 1.04$, $p = .365$.

Discussion

To begin with the significant effect of modality, the differences found between auditory and visual estimates reflect the fact that auditory stimuli were consistently judged as being of a longer duration than visual stimuli of the same physical duration. This finding was to be expected as it replicates a robust and widely reported effect throughout the timing literature, (Wearden, 1999; Wearden et al., 2006).

The significant interaction between modality and stimulus length found in the present experiment suggested such a clock speed/slope effect; this was confirmed by the subsequent slope analysis. Again this finding is consistent with the findings of previous studies such as those of Wearden et al. (1998) and Wearden et al. (2006), who also showed clock speed differences between visual and auditory stimuli.

The significant slope difference between estimates for auditory and vibrotactile stimuli also indicates that sounds are judged as longer than vibrations. Although it looks like estimates were slightly longer for vibrotactile than visual stimuli, there were no significant differences between estimates for visual and vibrotactile stimuli. This suggests that there is something special about auditory stimuli that creates this clock speed effect. To summarize, the speed of the internal clock appears to be faster for auditory stimuli than for either visual or vibrotactile stimuli. This is shown by higher estimates for auditory stimuli, with increasing differences at longer durations. Conversely, there appear to be no differences between estimates for visual and vibrotactile stimuli, and so clock speed could be considered to be approximately the same for these two modalities.

The lack of an intercept difference between any of the modalities suggests that there is no simple bias for over- or underestimating durations in the different modalities, nor is there any suggestion of a difference in the latency of stopping or starting timing, which would be interpreted as a difference in switch onset and offset latencies in the SET system.

EXPERIMENT 3

Temporal generalization

In Experiment 3, we used a temporal generalization task in order to ascertain whether timing in the vibrotactile modality exhibits the same scalar properties as those that had been previously demonstrated in the auditory and visual modalities. If timing of vibrations conforms to scalar timing then timing should show mean accuracy (the gradients should peak at the standard duration) and a constant coefficient of variation (we used two different standard durations to test this), and the functions from the two different standard durations should superimpose. Additionally, examination of the vibrotactile gradients should reveal whether the same asymmetry in the gradients is manifest as that in visual and auditory timing.

Method

Participants

A total of 12 psychology undergraduate students at the University of Manchester participated for course credit, which was not contingent on performance.

Apparatus

The apparatus was identical to that used in Experiments 1 and 2.

Procedure

Participants completed two separate tasks, the order of which was counterbalanced across all participants. The procedure for the two tasks differed only in the duration of the standard, which was either 400 ms or 800 ms. For each task, participants received 10 blocks, consisting of three presentations of the standard duration followed by nine test trials. The participant received three presentations of the standard following a display stating that the standard duration would be given. Between each presentation of the standard, there was a delay interval drawn from a uniform distribution running from 1,500–2000 ms, offset to onset.

Following the standard presentation, the participants received comparison vibrations whose duration was the standard duration multiplied by 0.25, 0.5, 0.75, 1, 1.25, 1.5, and 1.75. The standard duration was presented as a comparison duration three times, making nine trials in each block. At the start of each trial, participants were prompted to "press spacebar for next trial". The comparison stimulus was presented following a delay that was a random value picked from a uniform distribution running from 750−1,250 ms. After the comparison stimulus presentation, the participant judged whether or not the stimulus had the same duration as the standard, making a "Y" (yes) or "N" (no) response on the keyboard. No feedback about response accuracy was given. Following presentation of all comparison stimuli the next block began with presentation of the standard duration.

Results

Figure 4 shows temporal generalization gradients: the mean proportion of yes responses (identification of the presented comparison duration as the standard) plotted against comparison/standard ratio, for both the 400-ms and the 800-ms tasks.

Inspection of the data in Figure 4 reveals that the maximum proportion of yes responses (.57 and .53 for the 400-ms and 800-ms tasks, respectively) occurred at the standard duration. Thus the data fulfil the first criteria of scalar timing that performance should show mean accuracy. Secondly the temporal generalization gradients for the two tasks appear to superimpose (or at least differ very little) when plotted on this same relative scale (upper panel of Figure 4), suggesting conformity to scalar property of superimposition. Lastly the data from both tasks also appear to show the same asymmetry (more yes responses to durations longer than the standard than to those shorter than the standard) as has been found many times previously in the literature for visual and auditory temporal generalization.

These suggestions were confirmed by statistical analyses. A repeated measures ANOVA used standard duration (400 or 800 ms) and comparison/standard ratio (effectively the duration of the

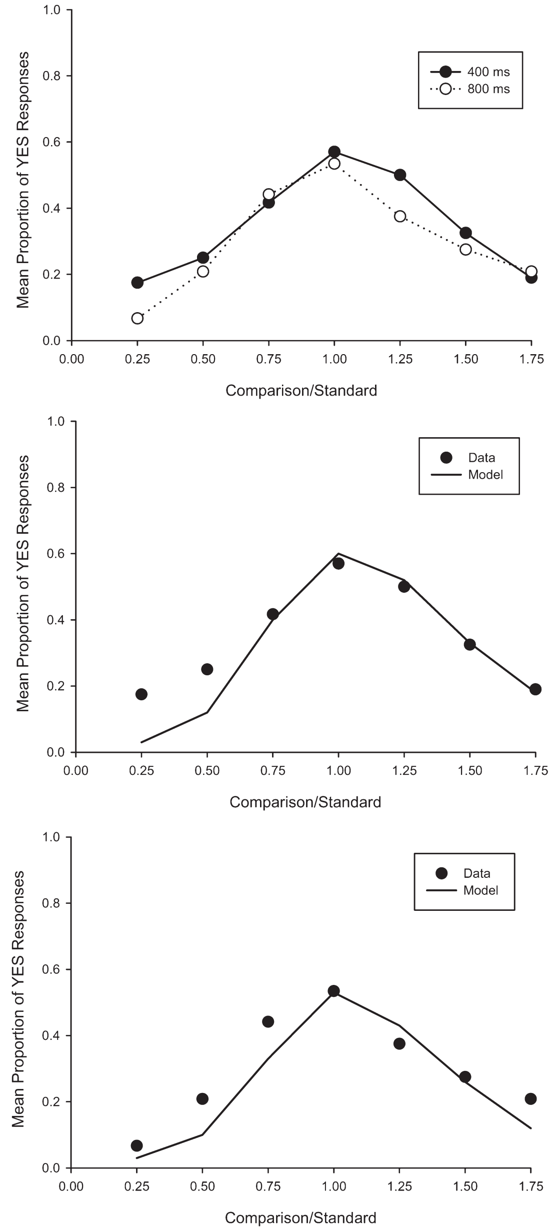

Figure 4. *Temporal generalization gradients: mean proportion of yes responses plotted against stimulus/comparison ratio of Experiment 3 (filled circles) and values predicted by best fitting modified Church and Gibbon (MCG) model (solid line). Upper panel: 400-ms and 800-ms standard conditions plotted on same graph for superimposition comparison: Middle panel: 400-ms standard condition with model fit. Lower panel: 800-ms standard condition with model fit.*

comparison) as within-subject factors. The effect of standard was borderline at $F(1, 11) = 3.46, p = .09$, indicating that the difference in the overall level of yes responses approached statistical significance for both tasks, but there was a highly significant effect of comparison/standard ratio, $F(6, 66) = 22.05$, $p < .001$, indicating that the participants were sensitive to comparison duration. There was no Standard Duration × Comparison/Standard ratio interaction, $F(6, 66) = 0.85$, $p = .54$, suggesting that the shape of the gradients for the two tasks did not differ significantly and thus fulfilling the key test for superimposition.

Symmetry of the gradients

Inspection of Figure 4 suggests some asymmetrical tendency in the data, with more yes responses elicited by the longer stimuli than by the shorter ones. However, this was not supported by statistical analysis. Firstly the mean number of yes responses to the 0.25, 0.5, and 0.75 comparisons were averaged and compared to the averaged mean number of yes responses to the 1.25, 1.5, and 1.75 comparisons. Although the mean number of responses was higher for the mean of the long comparisons than for the mean of the short comparisons in both conditions (400 short = 0.281; 400 long = 0.34; 800 short = 0.24, 800 long = 0.29), Wilcoxon tests failed to find any significant difference for either the 400-ms standard condition, $Z = -0.84$, $p = .40$, or the 800-ms standard condition, $Z = -0.905$, $p = .366$. We also made pairwise comparisons between each of the comparison durations (e.g., 0.25 with 1.75, 0.5 with 1.5, and 0.75 with 1.25); none of these comparisons revealed a significant difference.

Computer modelling

To explore the operation of the SET timing system when timing vibrotactile stimuli we conducted a number of computer simulations of temporal generalization performance. This enabled us not only to see whether vibrotactile data could be modelled successfully by SET, but if so then to reveal the best fitting parameters for the observed data.

The model used was the modified Church and Gibbon model (MCG; derived by Wearden, 1992, from Church & Gibbon, 1982), which has been demonstrated to give an excellent fit to human performance on temporal generalization tasks. In this model a yes response occurs when

$$|S^* - t|/t < b^*$$

where S is the sample drawn from reference memory, t is the just-presented duration, and b^* is a threshold value, which is variable from trial to trial. Both the memory of the standard and the threshold are represented as Gaussian distributions with means (S and b), c is the coefficient of variation of the memory representations, k is a distortion parameter (if $k > 1$ then S is stored as being longer than its actual duration, if $k < 1$ then it is stored as being shorter), and x the standard deviation of the representation of the threshold. Thus the model has four parameters b, c, k, and x. Previous computer modelling work has shown that x does not tend to vary, and almost all data can be fitted by keeping x constant at a value of 0.5 whilst varying the other parameters. We followed this convention in our modelling exploration.

This model was embodied in a Visual Basic program that generated 10,000 blocks of data for each simulation run. The parameters of c, k, and b were varied over a wide range to find those values that fitted each data set best, using a criterion of smallest total absolute deviation. Figure 4 shows the best fitting MCG models for the 400- and 800-ms tasks (middle and bottom panels of Figure 4). Table 2 shows the parameter values for the MCG model in these cases as well as the mean absolute deviation (MAD): the sum of the absolute deviations in proportions predicted by the model and those found in data, divided by 7 (the number of stimulus durations).

Computer modelling results

The MCG model was fitted to both 400-ms standard and 800-ms standard conditions. Figure 4 shows the real data points and also lines corresponding to points predicted by the model, and Table 2 shows the parameter values.

Table 2. *Best fit model parameter values for 400-ms and 800-ms conditions of Experiment 3*

Condition	*Parameter* c	b	k	*MAD*
400 ms	0.35	0.29	0.97	0.05
800 ms	0.37	0.24	0.97	0.05

Note: c = coefficient of variation of the memory for the standard duration; b = mean threshold value; k = mean of memory distribution of memory for standard duration; and MAD = mean absolute deviation, i.e., sum of absolute differences between prediction of model and data points divided by the number of data points (7).

Figure 4 suggests that the MCG model fitted the data very well in both cases with a MAD value of .005 for both conditions. Furthermore, as shown in Table 1 the parameter values needed to fit data from the two conditions were very similar. The fact that the coefficient of variation of the memory representation of the standard (c) was not affected by a change in the standard duration is a further example of conformity of the data to scalar timing theory. The parameter values needed for the threshold (b) and the distortion parameter (k) are both in line with those previously found for auditory and visual timing (Wearden, 1992). However, the value for the coefficient of variation of the memory representation for the vibrotactile data was 0.36 and 0.37 (for 400- and 800-ms standard conditions respectively), which is noticeably higher than the average value of 0.24 required to model visual and auditory timing (e.g., Wearden, 1992). Lastly, Figure 4 suggests that although the model was able to provide a good overall fit to the data it was generally less able to fit the data points for the comparisons shorter than the standard than those for the comparisons longer than the standard. This is likely to be a consequence of the lack of strong asymmetry in the real data.

GENERAL DISCUSSION

The temporal properties of vibrotactile stimuli were investigated in the present study. In Experiment 1, we investigated the relative sensitivity to time in the auditory, visual, and vibrotactile modalities. It was shown that auditory stimuli produce more accurate judgements than visual stimuli, replicating a consistent finding in the literature (Exner, 1895; Grondin et al., 1998; Hirsh & Sherrick, 1961). The interesting finding here was that vibrotactile difference thresholds were significantly higher than those for auditory stimuli, but were not significantly different to those for visual stimuli.

Our results and those of the rest of the timing literature suggest that auditory discriminations have some special status in that they consistently produce better sensitivity than visual ones and in our case also vibrotactile ones. The reason for this superior performance for auditory durations is still speculative. On the one hand, the characteristics of timing in different modalities are remarkably similar suggesting a common central timing mechanism. On the other hand, there is this persistent difference in sensitivity, which suggests that either the central timing mechanism operates differently for different stimuli (typically interpreted as a difference in clocks speed), or the input to the central timing system is different—that is, better attentional control to the stimulus onset and offset. However a difference in attentional control to the stimulus could not produce the difference in slopes that we observe both in our Experiment 2 and in previous studies (e.g., Wearden et al., 1998) without some additional theoretical assumptions. Our findings are also consistent with investigations of conflict between the sensory modalities; while vision typically dominates in spatial tasks, audition dominates in temporal tasks where it is argued it is a more “appropriate” modality (Welch, DuttonHurt, & Warren, 1986).

Perhaps one plausible but purely speculative ecological proposal is that our temporal discrimination of sounds is particularly acute due to the development of our language capacity; this would fit with the lower difference threshold for auditory stimuli, but again it is still difficult to conceptually ratify with slope effects.

Experiment 2 attempted to investigate clock speed effects using auditory, visual, and vibrotactile stimuli. The well-known difference in judgements of auditory and visual stimuli was again replicated here. Auditory stimuli were consistently estimated to be longer than visual stimuli of the same physical duration: Goldstone and Lhamon's (1974) "sounds are judged longer than lights" effect. Further, this effect was greater at longer durations, demonstrating a slope effect, which implies a difference in the speed of the internal clock for auditory stimuli (Wearden et al., 1998).

The novel finding from Experiment 2 was the expansion of the clock speed effect to the vibrotactile modality. Auditory stimuli were estimated as significantly longer than vibrotactile stimuli, and this effect again was greater at longer durations. In terms of explaining this finding, it would be parsimonious to suggest that the same mechanism that results in the difference between auditory and visual judgements also subserves this difference. Thus, the pacemaker of the internal clock system is running at a faster rate for the auditory stimuli than for the vibrotactile stimuli. This explanation, as described by Wearden et al. (1998) can account for both the difference itself and the fact that the difference is greater at longer durations.

To our knowledge, this is the first time that the relative clock speed of vibrotactile temporal judgements has been recorded. The same pattern as that seen with the difference thresholds was replicated in the verbal estimation task. Vibrotactile slopes were significantly flatter than those for auditory judgements but not significantly different from those of visual ones, although again there was a trend for the vibrotactile function to lie between the auditory and visual ones. The fact that this same pattern was seen in both experiments is strongly suggestive of a common explanation of both. Not only is it a well-established effect that sounds are judged longer than lights, but also that judgements of lights are more variable than those of sound. It has been suggested that the difference in variability may be due to the difference in clock speed.

Mathematically, a faster clock is a more accurate clock, and it allows for discrimination of a difference between two stimuli that measured by a slower clock would give the same output. For example, imagine that the task is to tell the difference between a 400-ms tone and a 450-ms tone. For the sake of argument let us compare two clock speeds: a fast clock producing 2 ticks per 10 ms and a slower clock producing 1 tick per 10 ms. The fast clock would record 800 ticks and 900 ticks for the two durations, a difference of 100 ticks, whilst the slower clock would produce 400 and 450 ticks, a difference of 50 ticks; thus the difference between the two stimuli is more likely to be detected with a faster clock. We can now extend this same argument to vibrotactile stimuli as the pattern of slope differences between the three modalities (Experiment 2) in the verbal estimation task corresponds to the pattern of difference thresholds in the weighted up-down task (Experiment 1).

Experiment 3 investigated whether performance on a temporal generalization task with vibrotactile stimuli would exhibit similar characteristics to that with auditory or visual stimuli. It was found that performance conformed to the prediction of SET with mean accuracy and scalar variance both exhibited. Additionally, the MCG model was found to give a very good fit to the data. The parameter values required to fit the data were generally in line with those typically required for visual and auditory timing, with the exception that the variability of reference memory (of the standard) was significantly higher for vibrotactile timing. This suggests that the long-term retention of vibrotactile-presented durations are either harder to maintain or are more poorly encoded than visual- or auditory-presented durations. The reason for this difference is unclear, though it may reasonably be argued that people are more practised with encoding, storing, and retrieving visual and auditory temporal sequences and durations than tactile ones.

Overall our experiments represent one of the first explorations of vibrotactile timing with modern stimulus control and nonexpert participants and under a theoretical framework. The general pattern of results suggests that people are able to time vibrotactile stimuli with a similar level of precision to that of visual stimuli and appear to time them with a similar clock speed to that of visual stimuli. Additionally the fact that the MCG model, which had previously been shown to give an excellent fit to data from visual and auditory timing, was also able to give a good fit to data from vibrotactile stimuli suggests that the same internal clock system subserves timing in all three modalities. This suggestion could be a fruitful area of future investigation to see how many other characteristics of performance vibrotactile timing shares with that of vision and audition.

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