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Speeding Up an Internal Clock in Humans? Effects of Click Trains on Subjective Duration

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Four experiments investigated the effect of trains of clicks (usually 5 s long and at 5 or 25 Hz) on subjective duration in humans, as previous research had suggested that such a manipulation would speed up the pacemaker of an internal clock by increasing participants' arousal. The four experiments used temporal generalization, pair comparison of duration, verbal estimation, and production of short durations. In all cases, preceding the durations to be judged by clicks changed their subjective length in a manner broadly consistent with the idea that pacemaker speed was increased, by an average of about 10%.

Recent findings have revived interest in the old idea (e.g., Hoagland, 1933) that some aspects of timing in humans might be mediated by an *internal clock*. One area of interest in this context is the apparent success of versions of *scalar timing theory*, a leading account of animal timing (Gibbon, 1977; Gibbon, Church, & Meck, 1984), as explanations of human timing on different sorts of tasks (e.g., Wearden, 1991a, 1991b, 1992, 1993, 1995; Wearden & Ferrara, 1995; Wearden & Lejeune, 1993; Wearden & McShane, 1988; Wearden & Towse, 1994; see also Allan & Gibbon, 1991; Fetterman & Killeen, 1992). Scalar timing theory, as is well known, proposes that the raw material for duration judgments comes from an internal clock of a pacemaker–accumulator type, so the application of this theory by implication also proposes an internal clock for humans.

Another relevant body of work is that resulting from the proposal of Treisman and colleagues (as expounded in detail in Treisman, Cook, Naish, & MacCrone, 1994, pp. 242–250, for example) that humans possess a "temporal pacemaker" consisting of several connected components. The first is a temporal oscillator that emits regular pulses at some fundamental frequency, but these pulses are gated to a second component, a calibration unit or "gain control," which can increase or decrease their frequency, before being emitted as output for further temporal processing mechanisms, such as counters or accumulators. External stimulus input can affect the operation of this system in two ways. One proposed effect is that external stimulation increases arousal, which then increases the gain of the calibration unit so as to effectively increase the rate of pulses emitted from the system. Thus, the number of pulses emitted per unit of time will increase when external stimulation is applied. Another effect is that repetitive stimulation at or near frequencies which are simple multiples (e.g., 1/5, 1/4, 2/3, 3/2, and so on) of the fundamental frequency of the temporal oscillator will perturb its action, causing local peaks and dips in the rate of output (e.g., Treisman et al., 1994, Figure 2).

Some experimental studies of this model have looked at the effect of different frequencies of repetitive stimulation (e.g., trains of clicks or visual flicker; see Treisman & Brogan, 1992; Treisman, Faulkner, Naish, & Brogan, 1990) on verbal estimation of the duration of visually presented stimuli. Other work has examined the effect of click trains on motor timing (Treisman, Faulkner, & Naish, 1992) and on the electroencephalographic correlates of performance while timing (Treisman et al., 1994). For purposes of our article, the essential feature of the work is the idea that stimulation increases the effective rate of the pacemaker and thus affects judgments of duration, that is, the first of the effects of external stimulation mentioned earlier. However, the focus of the articles of Treisman and colleagues has generally been on the specific interference with the temporal oscillator resulting from specific frequencies of stimulation (i.e., the second proposed effect of stimulation). In practice, this means that the data presented are often elaborately processed to examine whether local peaks and dips appear in measures of behavior (e.g., verbal estimates or response times), as a function of the frequency of external stimulation, and the more direct questions about timed behavior which are the focus of our article (such as whether verbal estimates of stimulus length change when the stimuli presented are preceded by trains of clicks, the present Experiment 3) are treated only in passing, if at all. However, one example of data, from Treisman et al. (1990, Figure 3) clearly showed that verbal estimates of visual stimulus duration were increased by accompanying the stimulus by a train of clicks, and this finding, attributed to a nonspecific arousal effect on the calibration unit, as described pre-

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viously, inspired the experimental methods used in our studies.

The general idea that arousal manipulations can change the rate of the pacemaker of an internal clock has been suggested by a number of diverse observations, ranging from the effects of changing reinforcement rates on timing behavior in animals (e.g., Fetterman & Killeen, 1995; Morgan, Killeen, & Fetterman, 1993) to the effects of changes in body temperature on time judgments in humans (Wearden & Penton-Voak, 1995), and we use this notion here in four experiments in which we attempt to influence humans' perception of short durations. If subjective event duration is changed by some manipulation while the duration timed itself remains physically constant, one possible interpretation (although not the only one) is that the manipulation used has changed the speed of an internal clock. For simplicity, we use this interpretation in our article, although, expressed more precisely, it is the speed of the pacemaker of a pacemaker–accumulator or pacemaker–counter mechanism that is changed.

Perhaps the clearest evidence that clock speed can be manipulated physically comes from drug experiments using animal subjects (e.g., Maricq, Roberts, & Church, 1981; Meck, 1983). The logic of these experiments generally uses the framework of scalar timing theory (Gibbon et al., 1984) to propose that animals time their behavior by using clock, memory, and comparison processes. For example, the representation of some critical duration, T, such as a time associated with reinforcement, is built up over a number of trials and is stored in some long-term reference memory. The representation of current duration, t, is derived by storing pulses from the pacemaker in an accumulator, which is gated to the pacemaker while the duration to be timed elapses, and this representation resides in some shorter-term working memory. In many animal timing tasks, participants must decide whether T and t are sufficiently close (e.g., Church & Gibbon, 1982) or make some judgment of similarity of t and more than one time value stored in the reference memory (as in the case of bisection; see Maricq et al., 1981). The drug experiments cited earlier are based on the notion of *state change:* If the reference memory is developed under a normal state, then increasing clock speed so that the current duration, t, is generated by a faster clock will produce a behavioral shift relative to the condition in which T and t are both generated with the clock running at the same speed (e.g., both normal or both fast). Thus, for example, the value of the *bisection point,* the duration judged halfway between two reference durations, is reduced if the reference durations are learned with the clock speed normal and tested with it fast, and increased if training and testing states are reversed (Maricq et al., 1981; Meck, 1983). When states are the same, however, the bisection point is not altered.

We used the idea of state change as the basic framework for the methodology of the experiments reported here. Our principal assumption, following Treisman et al. (1990), is that experiencing a brief period (1 to 5 s) of repetitive clicks of different frequencies (usually 5 or 25 Hz) is mildly arousing and that this arousal increases the speed of the internal clock. Thus, for example, a tone of some length t that follows a click train will be perceived as longer than one that is preceded by silence as the speed of the internal clock, and the passage of subjective time which is directly dependent on clock speed, increases. Consistent with this notion, a pilot experiment (reported in Wearden & Culpin, 1995) found that a tone was verbally estimated as longer when it was preceded by clicks than without clicks (a result duplicated in a much more elaborate form in our Experiments 3a and 3b).

As will be seen later, the four experiments reported here all used different methods. The aim of this broad-spectrum approach was to look at consistency of the effects of clicks on subjective time when time judgments were assessed in different ways and thus presumably were based on different decision mechanisms. Three of our experiments used short-duration tones as stimuli to be judged, although Experiment 3c also looked at judgments of the duration of visual stimuli; the fourth used a production paradigm, that is, response, rather than stimulus, timing. Three of the methods used (temporal generalization: Experiment 1; pair comparison: Experiment 2; interval production: Experiment 4) have analogues in procedures that can be used with animals, as discussed later, but Experiment 3, verbal estimation of duration, obviously has no animal analogue. All of the experiments use short (less than 1,200 ms) durations as the events to be timed, thus avoiding potential problems associated with chronometric counting in humans, a common precaution in studies testing internal clock models such as scalar timing with humans (see Wearden, 1991a).

Experiment 1

In Experiment 1 we used a variant of *temporal generalization.* The standard method, originally developed for rats by Church and Gibbon (1982) and modified for humans by Wearden (1991a, 1992), trained participants to recognize some particular duration as a standard. A series of comparison durations (including the standard as well as containing stimuli longer and shorter) was then presented, and participants judged whether or not each presented duration was or was not the standard. In experiments with humans, feedback as to response accuracy may or may not be given. The proportion of identifications of different durations as the standard when plotted against stimulus length yields a *temporal generalization gradient,* which is peaked at the standard in all cases so far studied (e.g., see Wearden & Towse, 1994, for some variants on the basic procedure).

Suppose, however, that the standard is learned with clock speed normal but that the comparison durations are presented when the clock is putatively fast. Such a manipulation will be expected to shift the temporal generalization gradient to the left, so that some stimulus slightly shorter than the standard should be maximally identified as the standard. For example, if a 400-ms standard is on average represented by N pulses from the pacemaker, speeding up the pacemaker will result in these N pulses being accumulated in some shorter period (e.g., 350 ms), which then becomes identified as the standard.

Experiment 1 used a 400-ms standard, with comparison durations spaced in 50-ms steps around it (i.e., the comparison durations were 250, 300, 350, 400, 450, 500, and 550 ms). The standard was always presented, identified as such and always preceded by silence, at the start of each block of stimuli, but the comparison stimuli were presented in three different states, preceded by 5 s of silence (a normal or control condition) or 5 s of clicks at either 5 or 25 Hz (two fast conditions). The experimental hypothesis predicts a leftward shift of the temporal generalization gradient in fast conditions compared with the normal control.

Method

Participants

Forty-two first-year psychology undergraduates 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 Hyundai 386STC (IBM PC compatible) computer, with a color monitor and keyboard, which served as the response manipulandum. The experimental programs were written using the MEL system (Micro Experimental Laboratory, Psychology Software Tools Inc.), which assures millisecond accuracy for stimulus and response timing. All auditory stimuli were produced by the computer's internal speaker.

Procedure

Each participant served in a single experimental session consisting of nine blocks of seven discrete trials. The nine blocks consisted of three blocks of each click rate (0-, 5-, and 25-Hz clicks). At the beginning of each block, the standard stimulus (a 500-Hz tone 400 ms long) was presented three times, with a period of 5 s of silence before each presentation. The monitor then displayed the message "End of Standards. Press spacebar for next trial." The seven comparison tones (250 to 550 ms in 50-ms steps) were presented in a random order that differed for each block. Each comparison stimulus was preceded by a 5-s click train of the specified frequency (5 or 25 Hz) or 5 s of silence (no clicks) depending on the block type. The same click frequency was used for all of the seven comparison trials in the block. Each click was a 1000-Hz tone presented for 10 ms, and the frequencies arranged (e.g., 5 or 25 Hz) were timed from onset to onset of clicks. The 5- and 25-Hz click trains were subjectively different, with 5-Hz clicks being repetition of distinct click stimuli, whereas the 25-Hz click trains were a subjectively continuous buzz. After the presentation of each comparison, the participant was asked if it had the same duration as the standard. The response was given by pressing the "Y(es)" and "N(o)" keys on the keyboard, but no feedback as to performance accuracy was given. The participant was then prompted to press the spacebar to initiate the next comparison stimulus until all seven had been presented and the message "End of Block" was displayed. A new block then began, with presentation of the 400-ms standard duration as described previously, until all nine blocks (3 with each click frequency [no clicks, 5, and 25 Hz] preceding comparison stimuli) had been presented. At the end of the ninth block, the message "End of Experiment. Thank you for participating" was displayed. The experimental session lasted about 30 min.

Results

When data from all 42 participants were averaged together (by averaging within each subject the data obtained from the three blocks with each click rate, then averaging these values together across participants), the resulting temporal generalization gradient from the no-click, control, condition (the proportion of YES responses, that is, identifications of a presented duration as the standard, plotted against stimulus length) was peaked at 400 ms (the standard duration), with stimuli both progressively shorter and longer than the standard producing progressively fewer and fewer YES responses. Inspection of the temporal generalization gradients from the 5- and 25-Hz click conditions suggested that the temporal generalization gradient was shifted to the left compared with the control condition, particularly when 5-Hz clicks were used. However, although analysis of variance (ANOVA) revealed a significant overall effect of tone duration (i.e., different length tones produced different proportions of YES responses: $F[6, 246] = 52.36, p < 0.001$), there was neither an overall significant effect of click rate, $F(2, 82) = 2.24, p = 0.11$, nor, more crucially, any significant Click Train × Stimulus Length interaction, $F(12, 492) = 0.98, p = 0.47$. The interaction is the critical statistic for demonstrating any changes in putative internal clock speed, as the hypothesized leftward shift in the temporal generalization gradient requires the click trains to have a different effect on responses to stimuli longer than the standard than on stimuli shorter than it.

However, inspection of data from individuals suggested that the group overall comprised two distinct subgroups. Consider only the control (no clicks) condition, in which all stimuli, both standards and comparisons, were presented preceded by 5 s of silence, and thus all stimuli were presumably represented by a normal pacemaker rate. In this control condition, 26 participants showed a temporal generalization gradient that either had its maximum proportion of YES responses at the 400-ms standard, or one in which the 400-ms stimulus tied for the maximum number of YES responses. These participants presumably had an accurate representation of the standard and will be described as *normally peaked* participants. The other 16 participants produced their maximum proportion of YES responses to some stimulus other than 400 ms. Their temporal generalization gradients were thus peaked in the "wrong" place, suggesting that participants had not developed an accurate representation of the standard. These participants will be referred to as *abnormally peaked*. It is important to note that this division into two subgroups was performed solely on the basis of performance in the 0-Hz, control condition and took no account of responding in the 5- or 25-Hz conditions.

Figure 1 shows temporal generalization gradients from no clicks, 5, and 25 Hz for normally peaked (upper panel) and abnormally peaked (lower panel) participants, plotted separately. Consider first the data from the normally peaked

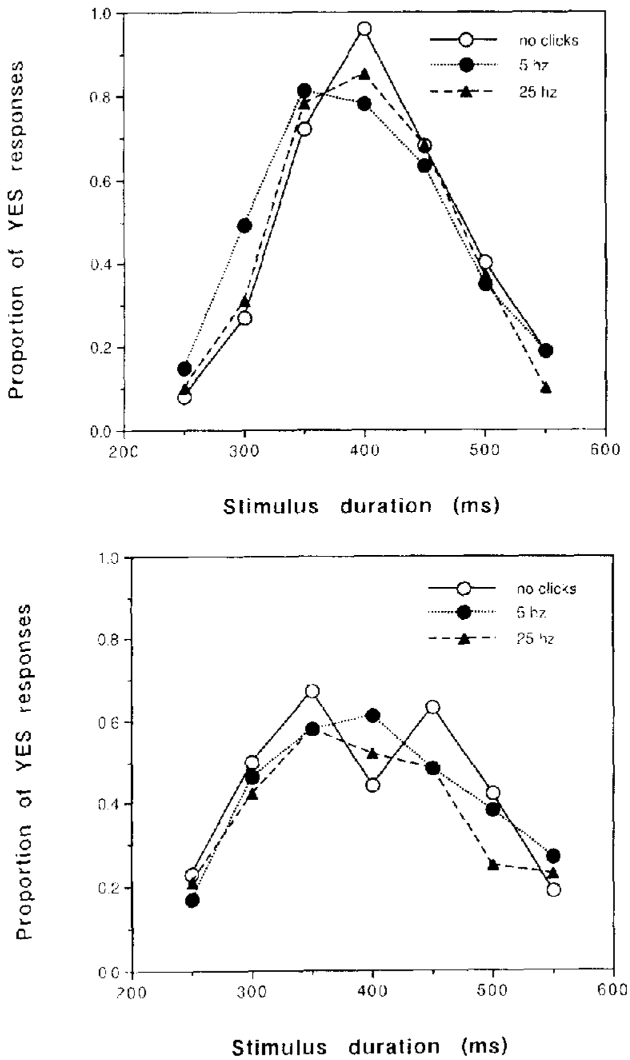

Figure 1. Temporal generalization gradients (proportion of YES responses, i.e., identification of a stimulus as the standard, 400-ms stimulus, plotted against stimulus duration) obtained in Experiment 1. Upper panel: averaged data from normally peaked participants. Lower panel: averaged data from abnormally peaked participants. In each panel, effects of preceding comparison tones by silence (no clicks) or by clicks at 5 or 25 Hz are shown separately.

participants. ANOVA found a significant effect of stimulus length, $F(6, 150) = 72.73$, $p < 0.001$, confirming statistically the fact, obvious in Figure 1, that participants made different proportions of YES responses to the different stimuli. There was, however, no significant overall effect of click trains, $F(2, 50) = 0.9$, $p = 0.41$, but there was a significant Click $\times$ Stimulus Length interaction, $F(12, 300) = 2.08$, $p = 0.02$, supporting statistically the impression gained by inspection of Figure 1 that the presence of click trains had shifted the temporal generalization gradient to the left. Comparison of the effects of 5- and 25-Hz click trains with no clicks revealed that the critical interaction was significant only for the 5-Hz clicks, $F(6, 150) = 3.86$, $p = 0.001$.

The abnormally peaked participants (data in lower panel of Figure 1) exhibited a significant effect of stimulus duration, $F(6, 90) = 7.1$, $p < 0.01$, but neither the overall effect of clicks, $F(2, 30) = 2.2$, $p = 0.13$, nor the Click $\times$ Stimulus Length interaction, $F(12, 180) = 0.98$, $p = 0.47$, was significant, indicating that click trains had no effect on judgments, nor were either of the individual click rate comparisons (5 and 25 Hz vs. no clicks) significant. Finally, we sought to determine whether the click trains produced any effect for different subgroups of the abnormally peaked participants. Inspection of the data from individuals of this type showed that there were three different patterns: peak at some stimulus value less than 400 ms (6 participants: *underpeakers*), peak at some value greater (7 participants: *overpeakers*), and two peaks, neither of which was at 400 ms (3 participants: *two-peakers*). We considered the group of two-peakers too small for statistical analysis but analyzed data from the other two subgroups. There was a significant effect of stimulus duration in both cases: underpeakers, $F(6, 30) = 9.09$, $p < 0.001$; overpeakers, $F(6, 36) = 5.54$, $p < 0.001$. The only other significant effect was an effect of clicks on the underpeakers, $F(2, 10) = 8.91$, $p = .006$, which inspection of the data suggested arose from a reduction in the proportion of YES responses at all stimulus values. In neither case was there a significant Stimulus Length $\times$ Click interaction, indicating that the shape of the temporal generalization gradient was not altered in either case.

Discussion

The results of Experiment 1 can be simply summarized: When comparison tones were successively compared with a standard, and representations of both the standard and comparison tones resulted from a normal speed clock, a substantial proportion of participants (the normally peaked subgroup) identified the standard correctly more frequently than any nonstandard stimulus was identified as the standard; thus their temporal generalization gradients peaked at the standard value. In these same participants, however, when the standard representation was generated by a normal clock speed and the comparison representations were generated by a putatively fast clock speed, the temporal generalization gradient was shifted significantly (albeit slightly) to the left, with a 350-ms stimulus being maximally identified as the standard in one condition, for example (see Figure 1). On the other hand, no such effect was obtained in data from people who failed to produce a peak of responses at the standard stimulus in the control condition (our abnormally peaked group, considered overall and in its various subgroups).

The most obvious interpretation of this result is that the speed of the pacemaker of the internal clock had been increased by the click manipulation, so that the subjective duration of tones preceded by click trains was lengthened relative to the subjective duration of the same tones preceded by silence. A leftward shift of a temporal generalization gradient of a slightly different sort from ours was obtained in a study by Maricq et al. (1981, Experiment 2), in which rats were trained on a peak procedure task (Catania, 1970; Roberts, 1981) with 20-s or 40-s standards without drug and were then occasionally tested after injection with amphetamine. This manipulation shifted the response rate versus elapsed time function slightly but significantly to the left (with the peak moving from 23.3 to 22.0 s in one case and from 43.2 to 41.3 s in the other), consistent with an effect of "speeding up the clock." A similar leftward shift of a response function somewhat analogous to a temporal generalization gradient was also demonstrated by Fetterman and Killeen (1995, Figure 10, p. 56) in response to a fourfold increase in reinforcement rate with pigeons, a manipulation proposed by Killeen and Fetterman's (1988) *behavioral theory of timing* to increase the rate of an internal pacemaker.

Experiment 2

The next procedure we used was based on the memory for duration paradigm used by Wearden and Ferrara (1993), which is a version of the *roving standard* procedure used in time psychophysics with humans (Allan, 1979). On each trial, participants received two tones (the first defined as the sample, the second as the comparison) separated by a 5-s offset-to-onset interval. These tones could have the same duration, or the comparison could be 100 ms shorter or longer than the sample. After offset of the comparison tone, participants were asked whether it was the same length as the sample, or was shorter or longer, although no feedback was provided after the response. Three types of trials can thus be defined in terms of the correct response: *equal* trials (comparison = sample), *short* trials (comparison < sample), and *long* trials (comparison > sample). In Experiment 2, the interval between the sample and comparison tones was either empty or filled with durations of clicks of various frequencies (5 to 25 Hz). The experimental prediction is that filling the interstimulus interval with clicks will subjectively increase the duration of the comparison tone (timed with a putatively fast clock) relative to the sample, which is always preceded by silence (and thus timed with a putatively normal clock). Such an increase in the subjective duration of the comparison should not, however, have the same effect on all trial types. On short trials, for example, any subjective lengthening of the comparison should make the discrimination between the sample and comparison more difficult and thus decrease performance accuracy. On the other hand, the very same subjective lengthening of the comparison will promote accuracy on long trials (cf. similar arguments in Wearden & Ferrara, 1993).

Method

Participants

Twenty-three University of Manchester undergraduates served as participants.

Apparatus

This was the same as that used in Experiment 1.

Procedure

Participants experienced a single experimental session consisting of four blocks of 15 trials. For all trials, the interval between the offset of the first (sample) stimulus and onset of the second (comparison) stimulus was 5 s. Each block comprised 5 trials of each type: equal, short, and long. Each of the three trials types was combined with each of five click frequencies, which were 0 (no clicks), 5, 9, 18, and 25 Hz, to give the 15 trials in the block. For different blocks the 15 trials were arranged in different random orders. All stimuli were 500-Hz tones produced by the computer speaker. On equal trials, the sample stimulus length was randomly chosen from a uniform distribution running from 300 to 500 ms (i.e., all values between 300 and 500 ms were equally probable) and was repeated as the comparison. On short trials, the sample was randomly chosen from a 400- to 500-ms uniform distribution, and the comparison was 100 ms shorter. On long trials the sample was chosen from a 300- to 400-ms uniform distribution and the comparison was 100 ms longer. Each trial began with a "Press spacebar for next trial" prompt, and this response was followed by a delay randomly chosen from a 1,000- to 3,000-ms uniform distribution. The trial events as described previously were then delivered. After offset of the comparison stimulus, participants were asked "Was the second tone longer (L), shorter (S), or equal (E) in length to the first?", and they responded with the indicated key (L, S, or E) on the keyboard. No feedback as to response accuracy was given. The experimental session lasted about 15 min.

Results

Figure 2 shows the number of correct responses for the

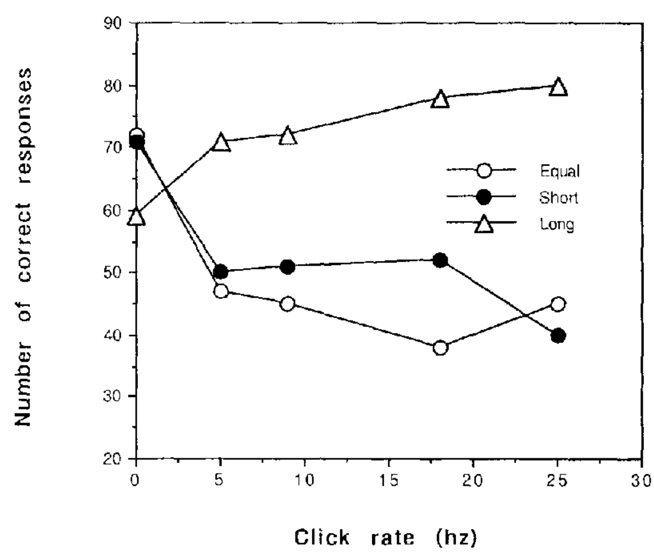

Figure 2. Number of correct responses on the pair comparison task (Experiment 2), plotted as a function of the click rate preceding the comparison tone. Data are shown separately for equal trials (comparison = sample), short trials (comparison < sample), and long trials (comparison > sample).

three trial types (equal, short, and long), plotted against click rate. Inspection suggests that (a) clicks affected performance accuracy, (b) the effect of clicks differed for the different trial types (decreasing accuracy on equal and short trials but increasing it on long trials, compared with no clicks), and (c) the different click rates did not produce different effects, which were, rather, between clicks (of any frequency) and no clicks.

These suggestions were confirmed by statistical analysis. Overall, there was a significant effect of trial type (equal, short, or long), $F(2, 44) = 12.50$, $p < 0.001$, and a significant interaction between trial type and click rate, $F(8, 176) = 7.33$, $p < 0.001$. For each trial type, clicks produced a significant effect on performance accuracy, $F(4, 88) = 8.3$ (equal), 4.93 (short), and 5.89 (long), all $p\text{s} < 0.001$, but linear contrasts showed that the effects in all cases were between clicks and no clicks rather than between different click rates. That is, none of the click rates produced any different effect from any other click rate, although all differed from no clicks.

Discussion

The results of Experiment 2 join those of Experiment 1 in suggesting that preceding a short tone by a train of clicks (from 5 to 25 Hz) increases its subjective length. The effect of clicks on the relative duration judgments was exactly that predicted by the supposition that subjective duration of the comparison tone had been altered; that is, the proportion of correct responses on short and same trials was reduced, whereas correct responding on long trials was increased. Thus, the clicks did not merely cause performance deterioration in all cases. The method used in Experiment 2, although similar to those used previously in studies of timing with both humans (Wearden & Ferrara, 1993) and animals (e.g., Fetterman & Dreyfus, 1986), may have two faults as a reliable and sensitive technique for demonstrating putative changes in subjective time. One problem is that the use of two stimuli in the same trial may give rise to time–order error effects (the fact that judgments of the relation between two successive stimuli depends on their order; Hellstrom, 1985; see also Wearden & Ferrara, 1993, for a review of time–order errors in duration judgments), which may complicate interpretation of effects of manipulations such as click trains. Another problem is that producing a "sandwich" of click trains between two tones as in Experiment 2 potentially confounds retrospective and prospective effects of the clicks: for example, our data could be interpreted equally well by supposing that the comparison tone was lengthened (prospective effect of clicks) or that the sample tone was shortened (retrospective effect). For both of these reasons, experimental techniques in which a single tone is presented on each trial may be simpler to use and interpret than those of Experiment 2.

Experiment 3

Experiments 1 and 2 provided evidence that preceding short tones by trains of clicks increases their subjective duration when this is assessed in two different ways. One interpretation of the effects of clicks on subjective time is in terms of change of pacemaker speed, but a more precise consideration of how pacemaker–accumulator clocks might operate suggests at least one other possibility, as Gibbon and Church (1984) showed. Suppose that participants possess a pacemaker that emits pulses at some rate, r, and that this pacemaker is connected to an accumulator through a switch that is closed (allowing pulses to flow from the pacemaker to the accumulator) when the event to be timed begins (e.g., the switch closure is triggered by stimulus onset in a case in which stimulus duration is to be timed) and opened again (interrupting the flow) when the event terminates. The switch closure and later opening may not be instantaneous but may require the latencies l_c to close and l_o to open. If some duration of length t is to be timed, then the number of pulses accumulating during t, N, is obviously $r(t - l_c + l_o)$. The number of pulses in the accumulator, on which subjective time is based, would obviously be increased, for a constant t value, either if r was increased (i.e., the pacemaker was speeded up) or if the balance between l_c and l_o was changed with constant r—for example, if the latency to open the switch and so to begin to accumulate pulses was shortened, the latency to close the switch and thus to stop accumulating pulses was lengthened, or both. If, however, both latencies were shortened or lengthened equally, there would be no effect on the number of pulses accumulated.

Can hypothesized effects of click trains on pacemaker speed be distinguished from effects on switch latencies? Inspection of the relation between N and t immediately shows that pacemaker rate, r, contributes to the slope of the function relating N and t (i.e., the slope of the relation between subjective and real time when different real-time values are presented), whereas effects on the switch contribute to the intercept of this function. Thus, if different time values are to be judged, increasing pacemaker speed should affect longer time values more than shorter ones, but switch effects should produce equal effects at all times. A technique that might be useful in distinguishing between these two possibilities is that of *verbal estimation of duration*, in which humans assign verbal labels (e.g., of a time in ms) to the length of events presented.

There is currently no formal theory of how verbal estimation is performed, but its use here is based on the idea that people can generate some verbal estimate of a real-time stimulus length (an estimate which may not be veridical either in individual instances or on average), probably on the basis of past extra-experimental experiences. Thus, the participant may respond with a particular verbal label when some stimulus of length t s is presented and N pulses from a pacemaker have accumulated. If the pacemaker is speeded up, the presentation of t results in a larger number of pulses than N accumulating; thus the participant's verbal estimate of the length of t increases.

If humans assign verbal labels to a range of stimulus durations, the function relating their mean verbal estimate to true stimulus length (which, to anticipate results presented later, is approximately linear) may be analyzed by regression to yield a slope and intercept measure. Following the arguments outlined earlier, changes in pacemaker speed should change the slope of the function, whereas changes in the latency to close the switch connecting the pacemaker and accumulator should change the intercept. Experiment 3 provides data intended to address this issue. It consisted of three subexperiments that were procedurally almost identical. In Experiments 3a and 3b, a range of tone durations was presented in which each tone was preceded by silence or by 1, 3, or 5 s of 5-Hz clicks. The difference between Experiment 3b and 3a was that 3b used a much wider range of stimulus durations than 3a, with a view to providing a better test of potential slope changes. Experiment 3c used an identical method except that the stimuli whose durations had to be estimated were visual. Experiment 3 attempted to address not only the slope change versus intercept change question but also the subsidiary ones of how long a click train needed to be to produce a change in subjective duration, and whether click trains would change the subjective length of both auditory and visual stimuli.

Because of their procedural similarity, Experiments 3a, 3b, and 3c are described and analyzed together, but in fact Experiments 3b and 3c were conducted after the results from Experiment 3a were obtained and were intended to address some ambiguities of interpretation left after the analysis of Experiment 3a.

Method

Participants

Experiment 3a. Thirty-four participants were recruited from the University of Manchester by advertisement. All were students at the university and were paid £5 (about $8) for an experimental session that lasted approximately 1 hr. Nineteen of these participants also served in Experiment 4.

Experiment 3b. Twenty-eight undergraduates participating for course credit served.

Experiment 3c. Sixteen undergraduates participating for course credit served.

Apparatus

This was the same as that used in Experiments 1 and 2.

Procedure

Experiment 3a. The task was explained to the participant by on-screen instructions, which were clarified where necessary by the experimenter. The participant was told that the experiment investigated the estimation of the length of tones and that all tones would be between 100 and 1,000 ms in length. Participants were also told that the tones to be estimated would sometimes be preceded by a train of clicks of varying durations. When the participant understood the procedure, the experimenter left and the participant was prompted to commence the session by pressing the spacebar.

Each trial commenced with a 5-s delay. This delay was silent, partially filled, or completely filled with a 5-Hz click train. Click trains of 1, 3, or 5 s were used. On trials in which the delay was partially filled with a click train shorter than 5 s (1 or 3 s), the clicks always directly preceded the tone to be estimated; for example, in trials with a 3-s click train the 5-s total delay began with 2 s of silence followed by 3 s of clicks and then the tone to be estimated. After the tone had been presented, the participant was asked to estimate its length in milliseconds, using the numeric keypad of the computer. Once the estimate was entered, the participant was prompted to start the next trial by pressing the spacebar.

An experimental block consisted of 10 stimuli whose length had to be estimated by the participants in each of the four conditions (no click train, 1-, 3-, or 5-s click trains): 40 trials in total arranged in a random order. The durations of the stimuli to be estimated were 323, 381, 419, 476, 507, 554, 620, 689, 737, and 773 ms. These stimulus lengths were arbitrarily chosen but were selected so that (a) they were not round values, that is, terminating in 50 or 00, and (b) there was the possibility that both increases and decreases in subjective duration that might be contingent on click train presentation might be manifested. Recall that the participants had previously been told that the minimum and maximum stimulus lengths were 100 and 1,000 ms. Because the shortest and longest stimuli presented were more than 200 ms away from these limits, there was the possibility of observing both a general increase and a decrease in stimulus length contingent on clicks. All stimuli were presented as 500-Hz tones delivered by the computer speaker. Each participant completed three blocks (120 trials) in an experimental session that lasted approximately 22 min.

Experiment 3b. The procedure was identical to that for Experiment 3a except that a wider range of stimulus durations was used. Values were 77, 203, 348, 461, 582, 767, 834, 958, 1,065, and 1,183 ms. Participants were told that all durations were between 50 and 1,500 ms in length.

Experiment 3c. For this experiment, the stimuli whose durations had to be estimated were 14 × 14 cm light blue squares, presented in the center of the computer screen. Stimulus lengths were 123, 281, 419, 576, 720, and 863 ms. As in Experiments 3a and 3b, each stimulus was presented preceded by no clicks or by 1, 3, or 5 s of clicks. Participants were told that all stimuli were between 75 and 1,200 ms in length.

Results

Data were first filtered to discard all estimates outside the range specified to participants (100–1,000 ms for Experiment 3a, 50–1,500 ms for Experiment 3b, and 75–1,200 ms for Experiment 3c). This resulted in the loss of only a few percent of the data and was done to eliminate the occasional erroneous estimate based on mistyping (7500 or 75, for example, when 750 was intended). The data were analyzed in two different ways: initially using verbal estimates, and then using slope and intercept values derived from regression analysis. First, repeated measures ANOVA was applied to verbal estimates in the four experimental conditions (0, 1, 3, and 5 s of clicks), with all conditions aggregated together. Then, individual ANOVAs on between-conditions comparisons (0 s vs. 1, 3, and 5 s; 1 s vs. 3 and 5 s; 3 s vs. 5 s) were conducted. Each of these ANOVAs yielded the following three measures: (a) an effect of stimulus duration, (b) an effect of click conditions, and (c) a Click × Stimulus Duration interaction. The first measure tests whether different stimulus durations give rise to different mean estimates, the second measure tests whether the different click conditions changed mean verbal estimates, and the third measure tests whether any effect of clicks differed at different stimulus lengths. If significant, this last measure may suggest a slope difference between conditions. Next, verbal estimates from each individual participant were regressed against stimulus length in each click condition (0, 1, 3, and 5 s of clicks) resulting in a slope and intercept value from each participant. These two values were entered into separate repeated measures ANOVAs, with analyses once again being conducted on all relevant comparisons (i.e., all click conditions together, 0 s vs. 1 s, and so on). The critical measure here was a between-conditions effect (i.e., Did different lengths of click trains produce significant changes in slope or intercept?).

To describe the very large number of results obtained from the ANOVAs in a clear and readable way requires some simplification. We therefore only occasionally provide full details of the F tests from the analyses and in other cases merely give associated p values (in a series of similar comparisons, this is sometimes the largest associated p, i.e., the least significant case). A result is described as nonsignificant if $p > 0.05$. In each subsection to follow, we further distinguish between analyses conducted on the verbal estimates themselves and those conducted on the slopes and intercepts derived from regression. One helpful simplification was the finding that in all comparisons conducted on mean verbal estimates in Experiments 3a, 3b, and 3c, there was a highly significant effect of stimulus length on estimate (all associated p values $< .0001$). These comparisons show that participants were highly sensitive to stimulus length, but the comparisons are not otherwise important and will not be mentioned further.

Experiment 3a

Data from one participant, who produced verbal estimates up to 10 times as long as others, were discarded. Figure 3 shows the effects of different lengths of click train (1 s: upper panel; 3 s: center panel; 5 s: lower panel) compared with the no-click condition.

Inspection of the data suggested that mean estimates increased as an approximately linear function of actual stimulus duration in all of the different conditions. Furthermore, estimates of tone length appeared slightly, but consistently, longer after clicks than in the absence of clicks. It also appeared that longer click trains (3 and 5 s) produced a larger effect on estimates than the shortest train (1 s).

Verbal estimates. An ANOVA of all conditions together showed a significant overall effect of clicks on estimates, $F(3, 96) = 35.91$, $p < 0.001$, and a significant Clicks × Stimulus Length interaction, $F(27, 864) = 1.67$, $p = .02$. Inspection of the graph shows that for the shorter durations, click trains seem to have a smaller effect than on longer durations. This effect is most clearly illustrated in the 1-s and 5-s click train conditions. All three click train lengths (1, 3, and 5 s) produced significant increases in mean estimates compared with the control condition: 1 s, $F(1, 32) = 23.27$, $p < 0.001$; 3 s, $F(1, 32) = 54.42$, $p < 0.001$; 5 s, $F(1, 32) = 58.17$, $p < 0.001$. But the Click × Stimulus Length interaction was significant, and then only marginally, for the 5-s click train, $F(9, 288) = 1.92$, $p = 0.049$. The effect of 1 s of clicks differed significantly from effects of both 3 and 5 s (1 vs. 3 s: $p < 0.001$; 1 vs. 5 s: $p < 0.001$), but the Click Rate × Stimulus Length interaction was never significant in these two cases: 1 vs. 3 s, $F(9, 288) = 1.83$,

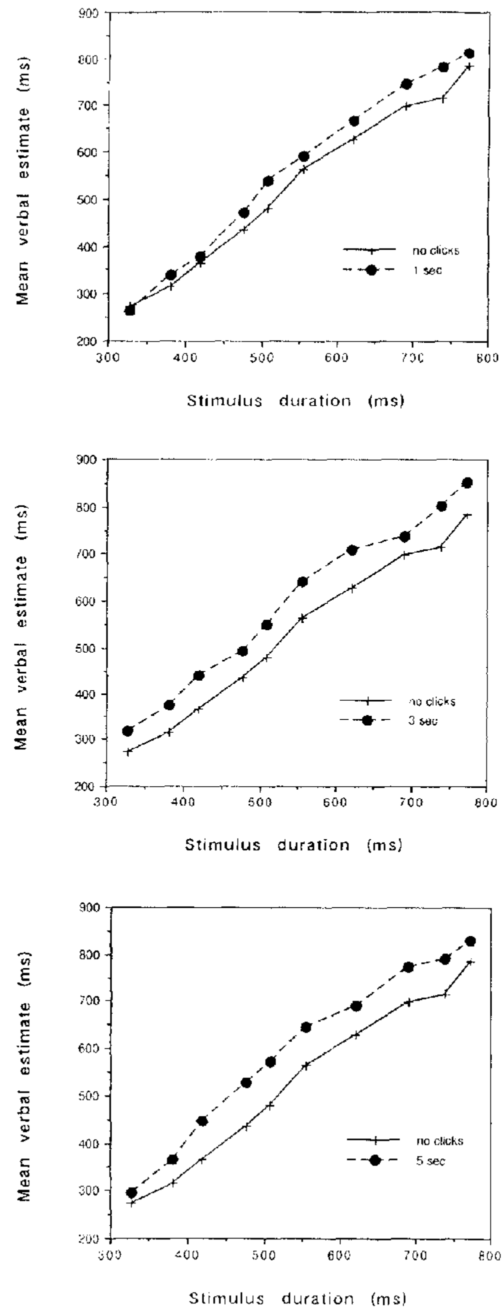

Figure 3. Mean verbal estimates (in milliseconds), plotted against stimulus length from Experiment 3a. Data are shown separately for tones preceded by silence (no clicks) and by different durations of 5-Hz clicks (1 s: upper panel; 3 s: center panel; 5 s: lower panel).

$p = 0.06$; 1 vs. 5 s, $F(9, 288) = 1.44$, $p = 0.17$. There was no overall difference between 3 and 5 s of clicks, however, $F(1, 32) = 0.01$, $p = 0.92$, but there was a significant Clicks × Stimulus Duration interaction, $F(9, 288) = 2.2$, $p = 0.02$.

Slope and intercept. An ANOVA on slope values derived from regression of data from individual participants found no significant overall effect of clicks, $F(3, 96) = 2.17$, $p = .096$, but 1 s of clicks produced a steeper slope than 0 s, $F(1, 32) = 5.49$, $p = .025$. None of the other comparisons (0 s vs. 1 or 3 s; 1 s vs. 3 or 5 s; 3 s vs. 5 s) were significant. Analysis of intercept values found an overall effect of clicks, $F(3, 96) = 12.70$, $p < .001$, with significant differences also being obtained in the 0-s versus 3-s and 0-s versus 5-s comparisons (both associated ps < .001) but no significant differences in intercept between the 0-s and 1-s conditions. Comparison of the effects of 1 s of clicks with both 3 s and 5 s of clicks yielded significant differences (largest associated $p = .003$) but no difference between 3 s and 5 s of clicks.

Experiment 3b

The upper panel of Figure 4 shows mean verbal estimates from the illustrative 5-s click condition and the no-click condition of Experiment 3b. Inspection suggests that not only did 5 s of clicks increase mean estimates but the effect was more pronounced at longer durations. As can be seen in the following section, this was supported by statistical analysis.

Verbal estimates. Analyzing all click conditions aggregated together revealed a highly significant overall effect of clicks, $F(3, 81) = 14.25$, $p < .001$, as well as a just-significant Clicks × Stimulus Duration interaction, $F(27, 729) = 1.51$, $p = .048$. Comparisons between the effects of different click train lengths revealed significantly higher verbal estimates, with 1, 3, and 5 s of clicks compared with no clicks (largest associated $p = .014$), as well as significant differences between the effects of 1 s of clicks and both 3 and 5 s of clicks (both $p < .001$), but no difference ($p = .22$) between the effects of 3 and 5 s of clicks. There was no significant Stimulus Length × Click interaction in the 0-s versus 1-s and 3-s comparisons, but the interaction was significant, $F(9, 243) = 2.53$, $p = .009$, in the 0-s versus 5-s comparison. There was no significant interaction in comparisons of 1 s of clicks with either 3 or 5 s, but there was a significant interaction in the 3-s and 5-s comparison, $F(9, 243) = 2.14$, $p = .03$.

Slope and intercept. An ANOVA of individual regression slopes found no overall effect, and no effect in the 0-s and 1-s comparisons, but higher slopes after 3 s in the 0-s and 3-s comparison, $F(1, 27) = 5.61$, $p = .025$, and a nearly significant slope elevation after 5 s in the 0-s and 5-s comparison, $F(1, 27) = 3.38$, $p = .077$. None of the other slope comparisons (1 vs. 3 and 5 s; 3 vs. 5 s) produced significant effects. There was no effect of click trains on intercept, either overall or in any of the comparisons.

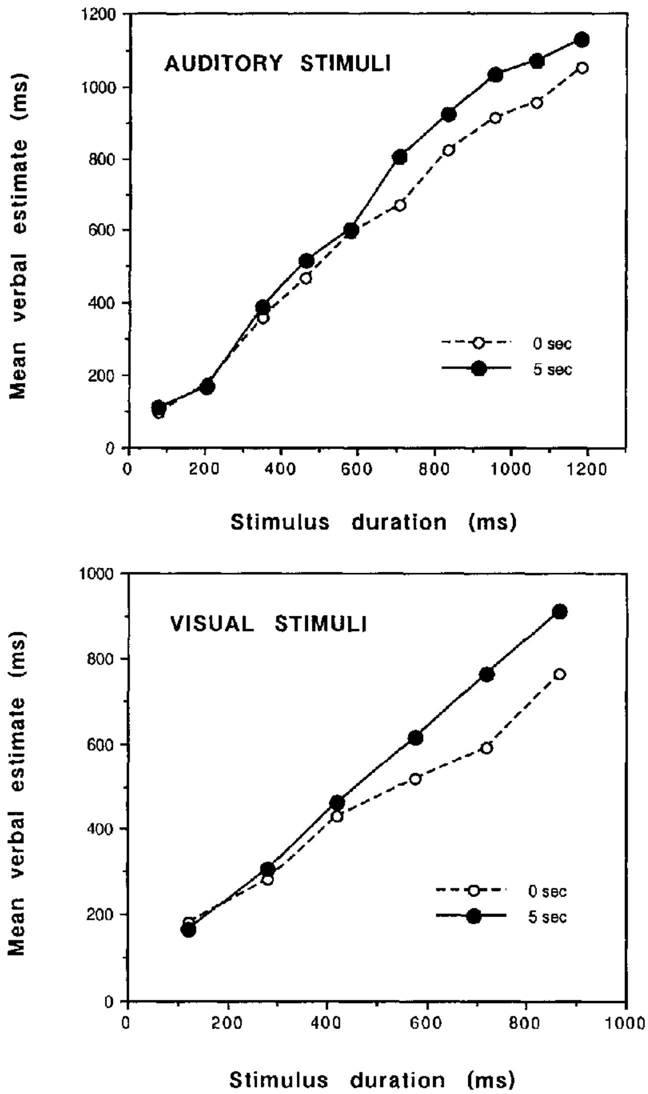

Figure 4. Mean verbal estimates (in milliseconds) plotted against stimulus duration for the 5-s click train and no-click (0 s) conditions of Experiments 3b (upper panel: auditory stimuli) and 3c (lower panel: visual stimuli).

Experiment 3c

The lower panel of Figure 4 shows mean verbal estimates from the illustrative 5-s and no-click (0-s) conditions of Experiment 3c. Inspection suggests that 5 s of clicks increased verbal estimates, with longer durations showing more pronounced elevation of estimates.

Verbal estimates. An ANOVA of all click conditions together found a highly significant overall effect of clicks, $F(3, 45) = 9.97$, $p < .0001$, and a Stimulus Duration × Click interaction that approached significance, $F(15, 225) = 1.61$, $p = .073$. Individual comparisons found significant effects of clicks in the 0-s versus both 3-s and 5-s comparisons (largest $p = .004$) but no significant effect in the 0-s versus 1-s comparison. There was a significant effect of clicks in the 1-s versus 3-s comparison but not in either the 1-s versus 5-s or 3-s versus 5-s comparisons. Significant Click × Stimulus Duration interactions were found in comparisons between 0 s and both 3 s and 5 s of clicks (largest $p = .008$) but not in the 0-s and 1-s comparison. None of the other comparisons (1 s vs. 3 and 5 s; 3 s vs. 5 s) yielded significant interactions.

Slope and intercept. Analysis of slopes derived from individual participant regressions found a highly significant overall effect of clicks, $F(3, 45) = 8.58$, $p < .0001$, and slopes were significantly higher after clicks in all comparisons of 0 s of clicks with 1, 3, and 5 s (largest $p = .005$). The 1 s versus 3 s yielded a just-significant difference, $F(1, 15) = 4.74$, $p = .046$, but no other comparisons were significant. No intercept effects, either overall or in any comparisons, were significant, although comparisons between 0 s and both 1 and 3 s of clicks yielded results that approached significance ($ps = .058$ and .072, respectively).

Discussion

Although there are a large number of results quoted in the previous section, summarizing them is straightforward. Preceding both tones (Experiment 3a and 3b) or visual stimuli (Experiment 3c) by trains of clicks increased their subjective length, with larger effects being obtained with 3 or 5 s of clicks than with 1 s, which often produced a nonsignificant increase with respect to the no-click condition. This suggests that the effect of clicks increases with between 1 and 3 s of clicks, with little effect of further increases in click train length being obvious.

The results also address the slope (speeding up the pacemaker) versus intercept (altering the switch) interpretations of click-induced increases in subjective duration. Results from Experiments 3b and 3c generally supported the speeding-up hypothesis, with significant Click × Stimulus Duration interactions being found in many comparisons of mean verbal estimates and significant effects of clicks on individual participants' regression slopes often being found (particularly in Experiment 3c). In contrast, analysis of regression intercepts from Experiments 3b and 3c never found a significant effect of clicks, although nearly significant differences sometimes emerged. At first sight, results from Experiment 3a appear to completely contradict this picture, as the effects on intercept were more common than effects on slope. However, the probable reason for the difference is that the intercept effects were an artifact of the restricted range of stimulus lengths used in Experiment 3, just over a 2:1 ratio of longest to shortest compared with the more than 15:1 ratio used in Experiment 3b and the 7:1 ratio of Experiment 3c. Furthermore, the stimulus set for Experiment 3a contained no stimuli as short as those used in the other two conditions. Inspection of typical mean estimate versus stimulus duration functions, such as those shown in Figure 4, immediately suggests that restricting the range of time values used, particularly to values in the upper part of the stimulus range, would obscure slope effects that were in fact present over the whole range. We do not, however, wish to rule out the possibility that the click train manipulations affect both pacemaker speed and the switch, as in our data near-significant differences in intercept that appeared in Experiment 3c. It should be noted, furthermore, that the reliability of attempts to dissociate switch and pacemaker speed effects by regression analysis probably depends on having an adequate range of durations to be judged, particularly if slope effects are to manifest themselves statistically.

A particularly noteworthy feature of Experiment 3 taken as a whole is that it demonstrated the effect of clicks on judged durations of both auditory and visual stimuli. Although direct comparisons are not possible because of the different stimulus values used, the data even suggest that the effect of clicks on visual stimuli were more pronounced than on tones, in that slope effects were more often significant with visual stimuli than tones, even with a smaller participant group. These results suggest that the effect of clicks does not depend on some auditory aftereffect or peripheral effect on the auditory system, but rather appears to be an effect on duration judgment per se, as the hypothesis that the click manipulation affects the operation of the internal clock, used for timing events in different modalities, would suggest. However, Experiments 1 to 3 have all looked at the effect of clicks on judgment of stimulus duration, and a further extension would be to examine any effect of clicks on the timing of a response.

Experiment 4

Experiment 4 used a *production* paradigm, in which participants produce some specified duration by responding and there is no stimulus duration to be estimated. In most common production paradigms used with humans (e.g., Wearden & McShane, 1988), participants initiate and terminate the interval to be produced, for example, by pressing on a button to start an interval and another button to terminate it, and the initiation of the production is at the participant's discretion. In our experiment, some productions were preceded by click trains, whereas others were preceded by silence. This meant that we needed to control the initiation of the production, so we developed a "production by waiting" method. A press on the computer's spacebar initiated a 5-s interval. During this interval, the duration to be produced was displayed on the computer screen, and in addition the interval was sometimes filled with clicks and sometimes silent. The 5-s interval terminated with a short and distinctive beep, and this beep started the duration to be timed. When the participant judged that the duration previously indicated had elapsed since the beep, he or she pressed the spacebar once, and the time from the offset of the beep to the spacebar press constituted the production.

Intervals to be produced ranged from 500 to 900 ms, and the production was sometimes preceded by clicks. If these clicks speed up the pacemaker relative to a control condition, then the production should be shortened, as is discussed further later. Another issue explored in Experiment 4 was the possible role of feedback in interval production.

Wearden and McShane (1988) showed that providing accurate feedback after each interval production in their experiment resulted in participants' exhibiting almost perfect mean accuracy (that is, if the interval to be produced was *t*, the mean time produced was also very close to *t*). In the absence of feedback, on the other hand, it is unlikely that mean times produced will be so accurately adjusted to required time, so in Experiment 4 both no-feedback and feedback conditions were used.

Method

Participants

Nineteen participants were used in both the feedback and no-feedback conditions of Experiment 4. They were recruited from around the university by advertisement. They were paid £5 for a 1-hr session in which they also participated in either Experiment 3 or another experiment not reported in detail here.

Apparatus

This was the same as that used in Experiments 1, 2, and 3.

Procedure

No-feedback condition. The participants were given on-screen instructions for the experiment that were clarified by the experimenter when necessary. Once the experimenter was satisfied that the task was understood, he left the cubicle and the participant was prompted to start the first trial by pressing the spacebar. This press initiated a 5,000-ms delay that was either silent or filled with a click train of 5 Hz or 25-Hz clicks. During this delay, the monitor screen displayed the time to be produced in the center of the screen. The durations that the participants were asked to produce were 0.5, 0.6, 0.7, 0.8, and 0.9 s. After the delay a distinct beep (a tone of 3,000 Hz presented for 75 ms) signaled the start of the time to be produced. The participants had been instructed to press the spacebar when the required time had elapsed. After the production, on-screen instructions told the participant to press the spacebar for the next trial.

There were seven blocks of 15 trials (105 trials in all). In each block a duration to be produced (5 in all) was presented with an unfilled delay, a 5-Hz click train, or a 25-Hz click train in random order. After all blocks had been completed, the participant was thanked for his or her participation and then asked to participate in the feedback condition after a short break. The no-feedback condition took about 12 min to complete.

Feedback condition. The procedure for the second condition of Experiment 4 was identical to that described previously, except for the addition of accurate feedback for the participant. This was presented on the screen (in ms) directly after each production and was displayed for 1,500 ms. Following the feedback, the participant was prompted to start the next trial with the spacebar. The presentation of all seven blocks in the feedback condition took about 14 min.

Results

Figure 5 shows the mean durations produced by the participants in the no-feedback (upper panel) and feedback (lower panel) conditions. ANOVAs in both cases (as well as the separate ANOVAs discussed later) revealed a significant effect of the required time on the time actually produced: no feedback, $F(4, 74) = 98.52, p < 0.001$; feedback, $F(4, 74) = 194.08, p < 0.001$. These effects merely show that participants were sensitive to the experimental contingencies and are not discussed further. In the no-feedback condition, there was a significant overall effect of clicks, $F(2, 36) = 6.05, p = 0.01$, and a Clicks × Time To Be Produced interaction, $F(8, 144) = 2.56, p = 0.01$. Separate ANOVAs were carried out on the 5- and 25-Hz click conditions compared with no clicks. In the 5-Hz condition

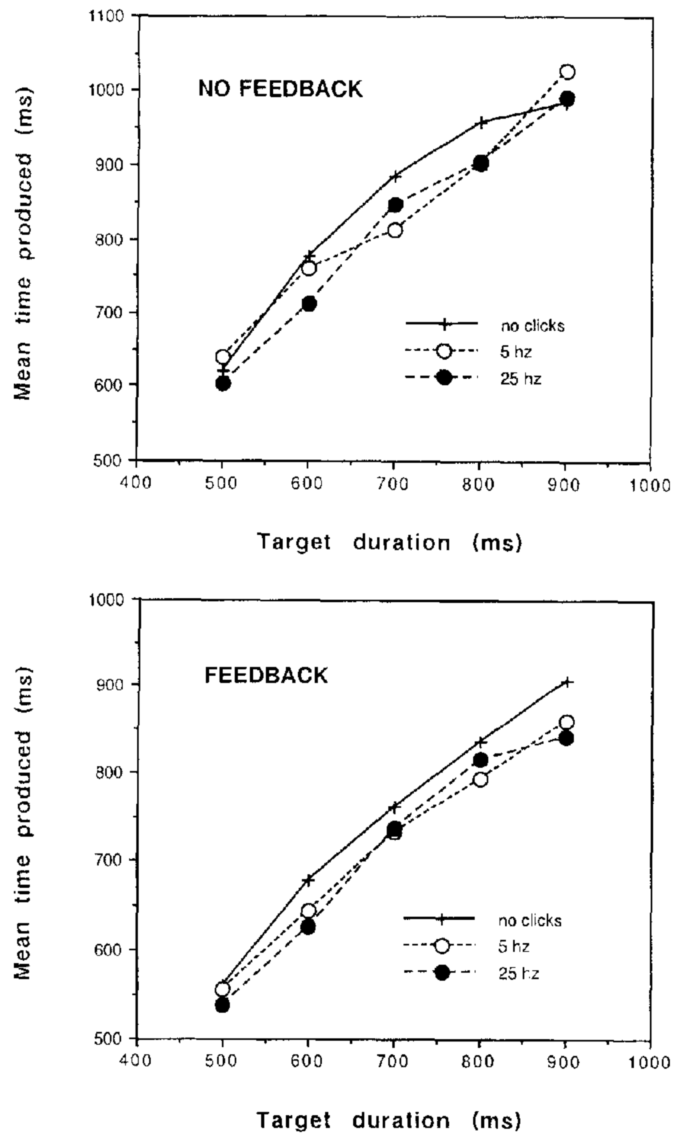

Figure 5. Mean times produced (in milliseconds), plotted against required time from the production study (Experiment 4). Upper panel: data from no-feedback condition. Lower panel: data from feedback condition. The mean times produced when the interval to be produced was preceded by silence (no clicks) or by 5- or 25-Hz clicks are shown separately in each panel.

there was no significant effect of clicks, although the results approached significance, $F(1, 18) = 3.67$, $p = 0.071$, but there was a significant Clicks × Time interaction, $F(4, 74) = 3.73$, $p = 0.008$. When 25-Hz clicks were used, on the other hand, the effect of clicks was significant, $F(1, 18) = 8.23$, $p = 0.01$, but the interaction was not, $F(4, 72) = 1.49$, $p = 0.21$. Comparison of the effects of 5- and 25-Hz clicks suggested a very slight difference between them, with an overall effect of click rate just failing to reach significance, $F(1, 18) = 4.28$, $p = 0.053$, and the Click Rate × Duration To Be Produced interaction just reaching it, $F(4, 72) = 2.53$, $p = 0.048$.

In the feedback condition, there was an overall significant effect of clicks, $F(2, 36) = 5.29$, $p = 0.01$, but no significant Clicks × Time interaction, $F(8, 144) = 0.90$, $p = 0.52$. Comparison of both the 5- and 25-Hz click conditions with no clicks revealed that both produced a significant effect of clicks: 5 Hz, $F(1, 18) = 5.35$, $p = 0.03$; 25 Hz, $F(1, 18) = 8.22$, $p = 0.01$. However, neither produced a significant Clicks × Time interaction. Comparison of the effects of 5- and 25-Hz clicks found neither an overall effect of click rate, $F(1, 18) = 0.36$, $p = 0.56$, nor any Click Rate × Duration To Be Produced interaction, $F(4, 72) = 1.16$, $p = 0.34$.

In general, the rather complex interactions described here tended to show that the effect of clicks was smallest at the shortest durations to be produced and tended to increase at longer durations, although in some cases (e.g., no-feedback conditions) the effect of clicks was again small at the longest durations.

The behavioral theory of timing (Killeen & Fetterman, 1988) proposed that increases in pacemaker speed should decrease behavioral variance; we used the coefficients of variation (standard deviation/mean) derived from individuals, averaged over the times they produced, to test this idea. Averaged values for coefficients of variation were (a) *no feedback:* no clicks, 0.32; 5 Hz, 0.27; 25 Hz, 0.30, (b) *feedback:* no clicks, 0.25; 5 Hz, 0.23; 25 Hz, 0.25. Thus, in the no-feedback conditions, coefficients of variation from the 5- and 25-Hz click conditions were on average smaller than from the no-click condition, and the effect approached statistical significance, $F(2, 36) = 2.96$, $p = .065$, whereas in the feedback conditions there was no suggestion of an effect of clicks, $F(2, 36) = 1.71$, $p = .19$. Comparison of coefficients of variation obtained from feedback and no-feedback conditions showed significantly lower coefficients of variation in the feedback conditions for all three comparisons (0, 5, and 25 Hz; largest associated $p = .02$). Thus, feedback reduced response variability around the mean time produced.

Discussion

Experiment 4 demonstrated an effect of clicks on subjective duration that differed in two ways from previous experiments. First, the effect was manifested in production, that is, the timing of a response, rather than in the judgment of stimulus duration. Second, the effect of the clicks was to shorten subjective duration of the timed event rather than to lengthen it as in the other experiments. Such an effect is completely compatible with a change in subjective time such as might arise from an increase in pacemaker speed. For example, suppose that in a normal state the participant accumulates N pulses from a pacemaker as a representation of some time t s that is to be produced. If the pacemaker speeds up, these N pulses occur in a shorter time; thus the time produced shortens. This is exactly the effect observed in Experiment 4 and the opposite effect to that observed on verbal estimation in Experiment 3.

Our use of both no-feedback and feedback conditions was motivated partly by the desire to examine both conditions and partly by the idea that effects of clicks on the two might differ. One possible effect of feedback is to "recalibrate" participants so that any effect of an increase in pacemaker speed is annulled. For example, suppose that in a normal state the participant accumulates N_1 pacemaker pulses during the t_1 s to be produced, and in the putatively fast state these N_1 pulses accumulate in some shorter time, t_2. If feedback is given after the production of t_2, the participant may compensate for the "undershoot" by accumulating some larger number of pulses, N_2, the next time that a production of t_1 is required. As has been seen, no such effect was evident in the data from the feedback condition of Experiment 4, in which preceding the intervals to be produced by clicks shortened them significantly. One reason for this may be that the intervals to be produced were randomly varied over trials in Experiment 4, rather than being presented in blocks (i.e., 12 consecutive productions of 0.5 s, as in Wearden & McShane, 1988). The possibility remains that if the durations had been presented in blocks, the participants would have gradually compensated for the effect of clicks in the feedback condition, as proposed earlier. The coefficients of variations, even from feedback conditions, were larger in Experiment 4 than in Wearden and McShane (1988); that is, performance was more variable around the mean, which suggests that presenting the same times to be produced in blocks does produce some behavioral differences from the procedure used here.

General Discussion

Results from the experiments presented here uniformly support the view that preceding short durations by trains of clicks changes their subjective length in a manner broadly consistent with an increase in the speed of the pacemaker of an internal clock. The results thus join others in the literature in supporting the view that humans possess a clock-like timing mechanism, the operation of which can be altered by physical manipulations involving arousal (see also Boltz, 1994; Treisman et al., 1990; and Wearden & Penton-Voak, 1995, for other examples).

Our method of using click trains to produce slight increases in arousal might be considered weak relative to techniques used to induce arousal changes that are used in areas such as psychophysiology (e.g., Wagner & Manstead, 1989), but it does have some positive features. For one thing, the method requires no special equipment or experimental conditions and, in principle, can be replicated in almost any laboratory (unlike studies of changes in body state such as those induced by temperature changes; see Wearden & Penton-Voak, 1995, for a review). For another, the method does not pose the ethical problems that can arise when participants are exposed without warning to disturbing or sexually provocative visual stimuli, which furthermore may produce arousal changes lasting many minutes or even hours. In addition, although the method might appear weak a priori, its effects on subjective time may not in fact be so weak. How much have our methods apparently changed subjective time compared with those used in some other studies, including those with animals?

In the following paragraphs, we attempt to compare our effects with those in some other studies representative of different methods used to influence the rate of subjective time in both humans and animals. We also attempt some sort of quantitative comparison, although the reader is cautioned that some of the values we quote were calculated from published figures or tables and so are approximate. A further qualification is that to provide a consistent comparative framework, we have made estimates of changes in the rate of subjective time on the basis of purely empirical timing functions. Fits of theoretical models to data can yield very different values from the ones we give (e.g., Fetterman & Killeen, 1995, p. 59) but depend on assumptions that cannot be applied to all of the studies we quote.

We consider first the data from studies with humans, starting with our own. Our Experiments 1, 3, and 4 can yield approximate values for the increase in the rate of subjective time. In Experiment 1, for example, the peak of the temporal generalization function shifted in one case from 400 to 350 ms, indicating about a 12% rate increase. In Experiment 3a, if all the verbal estimates are averaged together in each click train length condition, then 1 s of clicks increased the rate of subjective time by about 7%, whereas 3 s and 5 s of clicks produced an increase of about 13%. The same measures for Experiment 3b yielded estimated increases of 4, 9, and 11%, and for Experiment 3c values were 9, 17, and 19%. Averaging across all times produced in Experiment 4 likewise yielded increases of 2% (5 Hz) and 4% (25 Hz) in the no-feedback condition and 4–5% for both click rates in the feedback condition.

As mentioned in the introduction to this article, in the work of Treisman and colleagues the data presented are often elaborately processed, so it can be difficult to determine just what effect their manipulations had on directly observed behavior. However, one example (from Treisman et al., 1990, Figure 3, p. 713) suggests that click trains could increase verbal estimates of short tones by around 20% when high-frequency clicks were used, a larger effect than we obtained in our study, although one that is completely compatible with data from our Experiment 3. Wearden and Penton-Voak (1995) reviewed studies (some more than 60 years old) in which a range of different methods had been used to change humans' body temperature and thereby influence rate of subjective time. Wearden and Penton-Voak's Figure 1 (p. 133) shows that some manipulations increased rate of subjective time by more than 30%, with increases between 10% and 20% being common.

The use of amphetamine with rats was found by Maricq et al. (1981) and Meck (1983) to increase the rate of subjective time by about 10%, although another drug study using a bisection paradigm (Shurtleff, Raslear, Genovese, & Simmons, 1992) used scopolamine to produce increases in subjective time (as judged from shifts in the bisection point) of up to about 35% with the highest drug doses.

Fetterman and Killeen's (1995) categorical timing study provides what is probably the most straightforward and convincing example of an apparent increase in the rate of subjective time resulting from increases in the rate of reinforcement delivered to animals (pigeons in their case), with a fourfold increase in reinforcement rate producing between a 10% and 20% increase (depending on the method of calculation) in apparent pacemaker speed (see their Figure 10, p. 56). Similar results have been found in a number of other studies (e.g., Fetterman & Killeen, 1991; Haight & Killeen, 1991; Morgan et al., 1993), some conducted by a different research group (Bizo & White, 1994).

Overall, therefore, this brief and selective review of attempts to "speed up the internal clock" by various means suggests that our effects reported here are toward the weaker end of the range of possibilities, with manipulations that presumably radically affect the participant's physical state, such as large doses of drug (Shurtleff et al., 1992) or potentially dangerous increases in body temperature (reviewed in Wearden & Penton-Voak, 1995), having larger effects than manipulations of reinforcement rate, smaller doses of drug, or mildly arousing clicks.

In conclusion, our data show that a simple method can apparently reliably, if rather weakly, change the rate of subjective time in humans, most probably by speeding up the pacemaker of a pacemaker–accumulator type of internal clock. These experiments have only scratched the surface of experimental possibilities, but they suggest ways in which timing mechanisms that humans might share with animals, such as internal clocks of the type proposed by scalar timing theory (Gibbon et al., 1984; Wearden, 1991a), might be more fully explored.

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