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Click trains and the rate of information processing: Does "speeding up" subjective time make other psychological processes run faster?

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Click trains and the rate of information processing: Does "speeding up" subjective time make other psychological processes run faster?

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A series of experiments demonstrated that a 5-s train of clicks that have been shown in previous studies to increase the subjective duration of tones they precede (in a manner consistent with "speeding up" timing processes) could also have an effect on information-processing rate. Experiments used studies of simple and choice reaction time (Experiment 1), or mental arithmetic (Experiment 2). In general, preceding trials by clicks made response times significantly shorter than those for trials without clicks, but white noise had no effects on response times. Experiments 3 and 4 investigated the effects of clicks on performance on memory tasks, using variants of two classic experiments of cognitive psychology: Sperling's (1960) iconic memory task and Loftus, Johnson, and Shimamura's (1985) iconic masking task. In both experiments participants were able to recall or recognize significantly more information from stimuli preceded by clicks than those preceded by silence.

Keywords: Time perception; Reaction time; Iconic memory; Information processing.

Suppose a person is asked to perform a reading task as fast as they can and that they read 1 line each second, so reading 60 lines in a minute. Next, suppose that some manipulation is performed so that the subjective duration of the 60-s period is increased—that is, with the manipulation the person estimates the 60-s interval to have lasted longer than without it. When the subjective duration of the 60-s period is increased, can the person read (a) 60 lines, as before, (b) more than 60 lines, or (c) fewer than 60 lines? Answer (a) suggests that the rate of information processing does not vary when the rate of subjective time (i.e., as evidenced by the change in the duration estimate) is changed. Answers (b) and (c) imply, at the very least, some connection between information-processing rate and judgements of subjective duration. In the present article, we report a number of experiments employing a click-train manipulation that has been previously shown to increase the rate of subjective time, but our main focus of interest is how, or whether, this

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manipulation changes the time taken to make responses, or changes the quantity of information that can be remembered in two different memory tasks.

The general question treated in the present article is that of whether psychological processes take place in subjective time or clock-measured time. The distinction between the two is illustrated in the example given above: The clock-measured time is always one minute, but subjective estimates of this duration may vary. Studies of time perception conducted since the 1920s (Wearden & Penton-Voak, 1995) have investigated the idea that the rate of subjective time could be sped up, or slowed down, and in recent years a technique developed by Treisman, Faulkner, Naish, and Brogan (1990) has been routinely used in a number of studies. Treisman et al. (1990) demonstrated that accompanying stimuli with trains of repetitive clicks or flashes made people behave as if the stimuli lasted longer than when they were presented alone. Penton-Voak, Edwards, Percival, and Wearden (1996) demonstrated that the clicks need not be simultaneous with the stimuli to be judged but instead could precede them. For example, if people were asked to judge the duration of auditory or visual stimuli using a verbal estimation method (assigning verbal labels in ms to duration estimates), then both sorts of stimuli were judged as longer after clicks; see also Wearden, Edwards, Fakhri, and Percival (1998) and Wearden, Norton, Martin, and Montford-Bebb (2007).

The effects of click trains on measures of time perception were interpreted by Penton-Voak et al. (1996) in terms of a speeding up of the pacemaker of a putative pacemaker–accumulator internal clock of the sort suggested by Treisman (1963) and Gibbon, Church, and Meck (1984). The pacemaker–accumulator clock is proposed to operate as follows: When a stimulus to be timed begins, a switch connecting the pacemaker to the accumulator closes, allowing "ticks" to flow from the former to the latter. When the stimulus goes off, the switch opens, cutting the connection, so the accumulator contains the "raw material" for judgement of the duration of the stimulus, which can be subsequently used for various sorts of decisions about duration. The mathematics of pacemaker–accumulator clocks (discussed in Wearden et al., 1998) predict that if click trains do speed up the pacemaker, they will have a more marked effect at longer stimulus durations than at shorter ones, and this result has been found in a number of studies (e.g., Penton-Voak et al., 1996; Wearden et al., 1998). Further evidence that the clicks affected the rate of "accumulation" of subjective time came from another study in Penton-Voak et al., where people were required to produce time intervals of differing durations, with the intervals to be produced being preceded by clicks or silence. Now, a "speeding up" of the pacemaker should be manifested in shorter productions after clicks than without, and this was the effect found (see also Burle & Bonnet, 1997). Another study using a variant of Treisman's method showed that the rate of passage of subjective time could be increased in children as young as 3 by preceding visual stimuli by trains of flicker (Droit-Volet & Wearden, 2002).

This converging evidence suggests that the click trains make subjective time appreciate more rapidly than when the clicks are absent, an effect that Treisman et al. (1990) attribute to an increase in arousal occasioned by the clicks. Certainly, evidence suggests that decreases in arousal can make subjective time appreciate more slowly (Wearden, 2008; Wearden, Pilkington, & Carter, 1999), although increases in arousal are difficult to achieve in the laboratory without ethical problems, and arousal manipulations can have complex effects on duration judgements (e.g., Angrilli, Cherubini, Pavese, & Manfredini., 1997). However, whatever the mechanism is by which the click trains change subjective time, they have been found to produce significant effects in many published studies. The clicks thus provide a method of attack on the question posed earlier in this article, that of whether psychological processes take place in real (i.e., clock-measured) time or subjective time.

The experiments presented below use click trains to potentially influence performance on tasks not normally thought of as involving time perception. Two of these, however, use the time taken to execute responses as a performance measure, and these investigate effects on reaction time (Experiment 1) and the time taken to perform an arithmetic task (Experiment 2). Experiments 3 and 4 explore potential effects of clicks on memory performance, and here the response measure does not involve response time per se.

To anticipate results to be presented later, effects of clicks on performance in many of these conditions are found, so the question arises of whether these effects are linked to the well-known influence of clicks on time judgements (e.g., Penton-Voak et al., 1996; Wearden et al., 2007). To investigate this, comparisons are made in Experiments 1 and 2 between the effects of clicks and those of white noise, in order to control for the presence of any prestimulus noise. In unpublished studies in our laboratory it has been found that, in contrast to clicks, white noise never produced any effect on estimates of the duration of stimuli it preceded.

EXPERIMENT 1

Experiment 1 contrasted the effect of clicks or white noise (compared to silence) on a reaction time task. Penton-Voak et al. (1996; see also Burle & Casini, 2001) demonstrated that although click trains made estimates of the duration of subsequent tones or visual stimuli longer, they shortened times produced in an interval production task. Although the intervals produced were shortened, they were still much longer than the response times typically found on a reaction time task. The question that Experiment 1 poses is whether, when people are instructed to respond as fast as possible on 1-, 2-, or 4-choice reaction, preceding their responses by clicks (Experiment 1a) or noise (Experiment 1b) changes the reaction times compared with a silent condition—that is, did the clicks enable people to respond more quickly than they would be able to without the clicks?

Method

Participants

Undergraduate students from the University of Manchester participated in exchange for course credit, which was not contingent on performance. A total of 24 participated in Experiment 1a and 19 in Experiment 1b.

Apparatus

A Dell PC computer controlled all experimental events. The computer speaker produced the auditory stimuli, and instructions were displayed on the computer screen. The experiment was created using an E-Prime program (Psychology Software Tools Inc.). An E-Prime Serial Response box collected all reaction-time responses.

Procedure

Experiment 1a. Each participant served in two experimental sessions consisting of three block types (1-, 2- or 4- choice), and each block consisted of 20 trials (10 click and 10 no-click trials randomly intermixed). In one session the click rate was 5 Hz, and in the other session the click rate was 25 Hz. The order of these two sessions was counterbalanced across participants. At the beginning of each session, instructions appeared on the screen, and then participants were then asked to press the space bar to start the first trial. On each trial four boxes with a black outline and a white centre (80 pixels wide × 60 pixels high) appeared on the screen in a horizontal line. Each trial began with a 700-Hz beep of 25-ms duration followed by a 5-s period, filled either by silence or by a series of clicks of 5 Hz or 25 Hz (each click was 10 ms long), depending on the session type. This was then followed by a subsequent 700-Hz beep presented for 25 ms. Following the second tone there was a random delay (between 300 and 1,200 ms) before a small black cross (formed by two lines 11 pixels in length) appeared in the middle of one of the four boxes. The participant was instructed to react as quickly and accurately as possible on the appropriate button on the response box. After each response was made participants were asked to press the space bar on for the next trial to begin. In the first block type (the "one choice" condition), participants were asked to respond as fast as possible by pushing any one of the four buttons on the response box when the cross appeared in the centre of any one of the boxes presented on the screen. In the second block type (the "two choice" condition) participants were asked to respond on the far left key of the response box (marked 1) when the cross appeared in either of the two left-hand boxes and the far right key (marked 4) if the cross appeared in either of the two right-hand boxes. In the third block type (the "four choice" condition) participants responded on the appropriate key corresponding to each box—that is, key 1 for the left hand box, key 2 for box appearing second from the left, and so on. Each block lasted for 20 trials, and the order of the three blocks was randomized across participants. Participants were instructed when a new block type was beginning via instructions on the monitor and were asked to press the space bar to commence the first trial for the block. Throughout the experiment the participants rested their dominant hand on the response box with their fingers resting on each of the response keys.

Experiment 1b. The procedure was identical to that of Experiment 2a except that white noise was used instead of clicks, and only a single experimental session was carried out.

Results and discussion

Experiment 1a

Overall error rate in the choice reaction time conditions was extremely low: Out of 2,880 trials only 36 (1.25%) were error trials, and these were excluded before data analysis. Mean reaction times for 5-Hz, 25-Hz, and no-click conditions and the three different block types (1-, 2-, and 4-choice) are plotted in the upper two panels of Figure 1, where the upper panel shows data from the 5-Hz condition and the lower panel data from the 25-Hz one. Inspection of the data suggests that (a) reaction times increased markedly as the number of choices increased, and (b) in

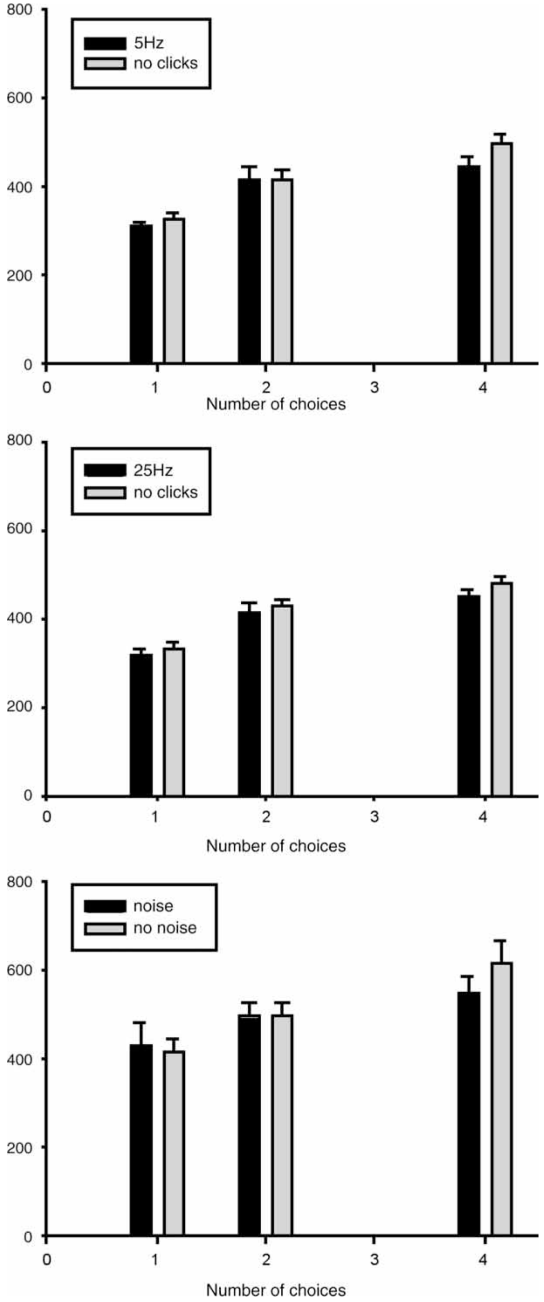

Figure 1. *Mean reaction times from Experiments 1a and 1b. Vertical bars show standard error of the mean. Upper panel: mean reaction time plotted against number of choices for no-clicks and 5-Hz clicks conditions. Centre panel: mean reaction time plotted against number of choices for no-clicks and 25-Hz clicks conditions. Bottom panel: mean reaction time plotted against number of choices for no noise and noise conditions.*

general both 5-Hz and 25-Hz clicks made reaction times quicker. These suggestions were supported by statistical analysis.

Repeated measures analyses of variance (ANOVAs) were used for both the 5-Hz and 25-Hz conditions, with one factor being number of choices (1, 2, or 4) and the other factor being the presence or absence of clicks. For the 5-Hz conditions, there were significant effects of number of choices, $F(2, 26) = 28.99$, $p < .001$, and presence or absence of clicks, $F(1, 23) = 5.55$, $p < .05$, and a significant clicks/no clicks by choice number interaction, $F(2, 46) = 4.71$, $p < .05$. For the 25-Hz condition there was a significant effect of number of choices, $F(2, 46) = 43.50$, $p < .001$, and presence or absence of clicks, $F(1, 23) = 6.35$, $p < .05$, but the interaction between these factors was not significant, $F(2, 46) = 1.14$. Inspection of the data in Figure 1 suggests that the interaction in the 5-Hz condition, which was probably responsible for the interaction obtained in the overall ANOVA, was due to the lack of effect of clicks in one or more of the choice conditions when the click rate was 5 Hz. We conducted t tests to explore this interaction. This revealed a significant difference between the reaction time of the clicks and no clicks in the 4-choice condition, $t(23) = -2.39$, $p < .05$, but not in the 1-choice, $t(23) = -1.43$, or 2-choice conditions, $t(23) = -0.28$.

Experiment 1b

Overall error rate in the choice reaction time conditions was extremely low: Out of 1,140 trials only 22 (1.91%) were error trials, and these were excluded before data analysis. Mean reaction times for the white noise and no-noise conditions and the three different block types (1-, 2-, and 4- choice) are plotted in the bottom panel of Figure 1. Inspection of the data suggests that (a) reaction times increased markedly as the number of choices increased, and (b) there was little or no difference between the reaction times for the white noise and no-noise conditions. These suggestions were supported by statistical analysis.

A repeated measures ANOVA was used with one factor being number of choices (1, 2, or 4) and the other factor being the presence or absence of white noise. There was a significant effect of number of choices, $F(2, 36) = 11.38$, $p < .001$, but no significant effect of the presence or absence of white noise, $F(1, 18) = 0.77$, $p = .39$. There was also no significant white noise/no noise by choice number interaction, $F(2, 36) = 0.95$, $p = .40$.

As there were slightly differing numbers for Experiments 1a and 1b we calculated the effect sizes using partial eta squared values. The results show that the level of effect size is so small that the inclusion of a small number of additional participants would clearly not have changed a nonsignificant effect into a significant one. For Experiment 1a (5 Hz), $\eta^2 = .16$ (clicks), .80 (choice), and .12 (Clicks × Choice). For Experiment 1a (25 Hz), $\eta^2 = .19$ (clicks), .79 (choice), and .05 (Clicks × Choice). For Experiment 1b (white noise), $\eta^2 = .04$ (noise), .57 (choice), and .09 (White Noise × Choice).

The results shown in Figure 1, and the statistical analysis that accompanies them, demonstrate two clear effects. One is that reaction time on our task increased markedly with the number of choices and that this effect was found on trials preceded by clicks of both frequencies, white noise, and trials preceded by silence. This result is, of course, a classic one (Hick, 1952) and occasions no surprise, but does show that our choice procedures appeared to produce the "normal" results in all cases. More interestingly, we found that preceding reaction time trials with click trains in general made reaction times faster. In four of our six conditions, the exceptions being the 1- and 2-choice reaction time with 5-Hz clicks, the mean reaction time after clicks was faster than that on no-click trials, and there were significant overall effects of both 5-Hz and 25-Hz clicks. The effect of clicks is unlikely to be due to the end of the click train warning participants that the reaction time phase of the trial is about to start, as a cue to this effect was presented even on no-click trials, and no effect of white noise was found, even though any potential for cueing seems equal in this condition. It seems therefore that the click trains, which in other studies have been shown to make stimulus durations appear longer (Penton-Voak et al., 1996; Wearden et al., 1998, 2007) and to make intervals produced shorter (Burle & Bonnet, 1997; Burle & Casini, 2001; Penton-Voak et al., 1996), also increase speed of reaction on a task that does not involve time perception per se.

EXPERIMENT 2

Having found a facilitatory effect of clicks on a low-level perceptual-motor reaction time task in Experiment 1 we sought to ascertain whether this effect would generalize to a more complex task where once again reaction speed was the critical behavioural measure, but which was expected to produce longer response latencies. In Experiment 2 we used a mental arithmetic task, with Experiment 2a using a click-train manipulation and Experiment 2b white noise. The overall methodology was identical to that of Experiment 1, but instead of a cross being presented in one of four squares, a mathematical addition problem, complete with a potential answer, was presented. The participants' task was simply to decide as quickly as possible whether the answer given on the screen was correct or not. As in Experiment 1 we might expect the reaction times to be significantly quicker for the problems presented after a click train than for those presented after a period without clicks, if the clicks speed up information-processing rates. As in Experiment 1a, the present Experiment 2a investigated two frequencies of click train (5 Hz and 25 Hz) and in addition also created two levels of task difficulty, by varying the number of items to be summed between two and three.

Method

Participants

University of Manchester undergraduates participated in exchange for course credit, which was not contingent on performance. A total of 34 served in Experiment 2a (click trains) and 28 in Experiment 2b (white noise).

Apparatus

The apparatus was the same as that in Experiment 1.

Procedure

Experiment 2a. All participants received the mental arithmetic task twice with the only difference between the two conditions being click frequency, which was either 5 Hz or 25 Hz. The order of these two frequencies was counterbalanced across the subjects. In both cases the trials were preceded either by a click train or by an equivalent period without clicks. There were two trial conditions (clicks and no clicks) and two further subconditions of *easy* and *hard* additions. In the clicks condition participants were asked to look at a fixation cross in the centre of the screen and to begin the trial by pressing the spacebar. Participants were then presented with a 25-ms beep (700 Hz), followed by a 5-s click train (5 Hz or 25 Hz). A further 25-ms beep (700 Hz) ended the click train, which was followed by a random delay between 300 and 1,200 ms. The fixation cross remained on screen throughout this process. A display then appeared on the monitor in place of the cross, presenting participants with an addition problem composed of either a correct or an incorrect addition (such as "$2 + 9 = 11$" or "$2 + 9 = 13$"). Participants had to respond whether the sum was correct or incorrect by pressing "Y" (for correct answers) or "N" (for incorrect answers) on the keyboard. Participants were instructed at the beginning of the experiment to keep one finger on each of these two keys throughout the trials. Incorrect responses were accompanied by feedback (a "beep") to maintain the participants' focus. Once a response had been made the trial was over, and participants began the next trial after a prompt to press the spacebar when ready to continue.

In the no-clicks condition, trials were performed in an almost identical manner, with the exception that 5 s without clicks was used in place of the 5-s click train, as in Experiment 1a.

The addition problems themselves were randomly generated by the E-Prime program, which displayed either the correct answer to the sum or an incorrect random answer drawn from a distribution of integer values that fell within 4 of the correct answer. The probability of either condition arising (correct or incorrect) on each trial was .5. There were two experimental conditions, *easy* and *hard*. In the *easy* condition the additions were composed of two single digits (of random numbers generated between 1 and 9) and an answer (e.g., "$5 + 6 = 11$", or "$5 + 6 = 14$") whereas *hard* additions involved additions of three single digits (e.g., "$5 + 6 + 2 = 13$", or "$5 + 6 + 2 = 11$"). Thus, there were four experimental conditions; "easy clicks", "easy no clicks", "hard clicks", and "hard no clicks", and this entire procedure occurred twice, with the click frequency being varied over values of 5 and 25 Hz.

Participants received 10 trials in each experimental condition (40 in total), the ordering of which was randomized throughout the experiment. This was to ensure against such effects as task learning and experimental fatigue. Participants' response time and accuracy were measured on all trials.

Experiment 2b. The procedure was identical in all respects to that of Experiment 3a, except that (a) clicks were replaced by white noise, and (b) the participants completed 80 trials, 20 in each condition (easy no-noise, easy white noise, hard no-noise, hard white noise), in a single experimental session.

Results and discussion

Experiment 2a

The mean response times and standard errors for each of the experimental conditions are shown in the upper two panels of Figure 2, with data from the 5-Hz conditions in the upper panel and those from the 25-Hz conditions in the middle one. Inspection of the data suggests that, first, the response times for all of the *hard* arithmetic problems were clearly longer than those for the *easy* ones. Secondly there appeared to be a clear reduction in reaction time in the click trials relative to the no-clicks trials for the 5-Hz conditions, but no such effect for the 25-Hz conditions. These suggestions were supported by the statistical analysis.

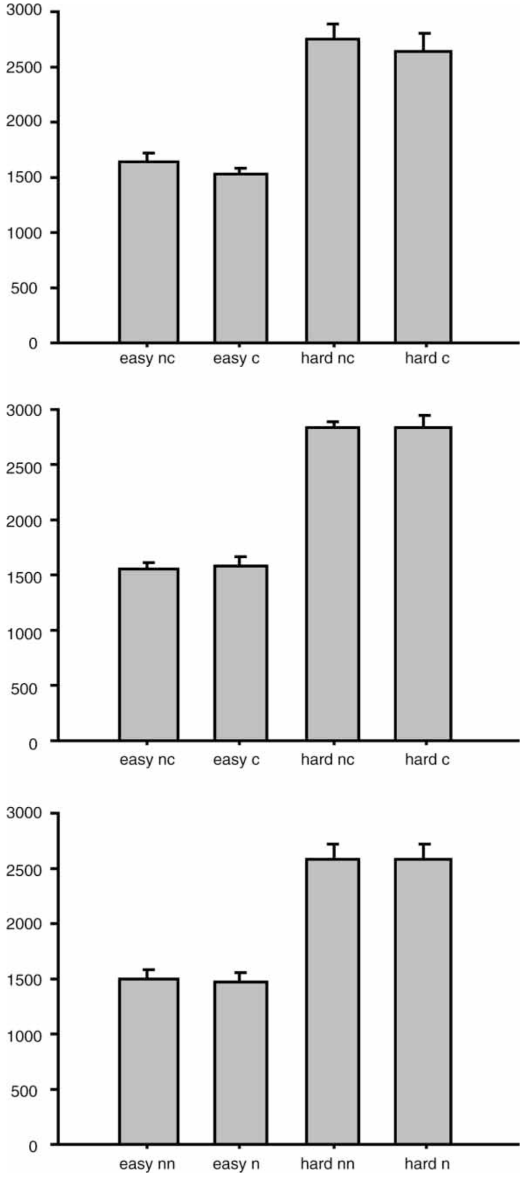

Figure 2. *Mean response times from Experiments 2a and 2b. Vertical bars show standard error of the mean. Data are shown separately in each panel for easy and hard arithmetical problems, and for the different conditions. Upper panel: 5-Hz clicks; centre panel: 25-Hz clicks; nc = no clicks; c = clicks. Bottom panel: no noise (nn) and noise (n) conditions.*

We analysed data from the 5-Hz and 25-Hz conditions separately. Taking the 5-Hz condition first, a repeated measures ANOVA used presence or absence of clicks and arithmetical difficulty (*easy* or *hard*) as within-subject factors. There were significant effects of clicks versus no clicks, $F(1, 33) = 4.24$, $p < .05$, and *easy* versus *hard*, $F(1, 33) = 210.00$, $p < .001$, confirming both an effect of clicks and that reaction times were significantly faster for the *easy* than for the *hard* conditions. There was no significant Clicks (clicks/no clicks) × Difficulty (*easy*/*hard*) interaction, $F(1, 33) = 0.012$, $p = .92$. For the 25-Hz conditions, there was no significant effect of clicks versus no clicks, $F(1, 33) = 0.033$, $p = .57$; there was, however, a significant effect of *easy* versus *hard*, $F(1, 33) = 179.72$, $p < .001$, indicating that reaction times were significantly faster for the *easy* than for the *hard* conditions. There was no significant Clicks (clicks/no clicks) × Difficulty (*easy*/*hard*) interaction, $F(1, 33) = 0.11$, $p = .745$.

Responses were also examined for their accuracy across different conditions. A paired-samples *t* test was performed, examining the differences in mean number of errors between the clicks (0.82) and no clicks (0.91) conditions of the 5-Hz procedure. The results indicated no significant difference, $t(33) = -0.44$, $p = .66$, between these two conditions. The same analysis on the 25-Hz procedure yielded the same result, with the mean number of errors in the click (1.03) and no click (1.21) conditions not differing significantly, $t(33) = -1.03$, $p = .31$. The differences between the mean number of errors in the 5-Hz (1.74) and 25-Hz (2.24) procedures overall was also nonsignificant, $t(33) = -1.69$, $p = .10$.

Experiment 2b

The mean response times and standard errors for each of the experimental conditions are shown in the bottom panel of Figure 2. Inspection of the data suggests that, first, the response times for all of the *hard* arithmetic problems were clearly longer than those for the *easy* ones and, secondly, that there appeared to be no difference in reaction time on the white noise trials relative to the no-noise trials. These suggestions were supported by the statistical analysis.

A repeated measures ANOVA was used with one factor being task difficulty (*easy* and *hard*) and the other being the presence or absence of white noise (white noise and no noise). There was a main effect of task difficulty, $F(1, 27) = 251.02$, $p < .001$, but no main effect of noise, $F(1, 27) = 0.019$, $p = .67$, nor interaction between task difficulty and the presence or absence of noise interaction, $F(1, 27) = 0.05$, $p = .82$.

Overall, therefore, participants' response times on the arithmetic task were significantly reduced by clicks, but only when click frequency was 5 Hz. The effect of click frequency on subjective time judgements was explored systematically by Treisman et al. (1990) and, less systematically, by Penton-Voak et al. (1996). Treisman et al.'s data suggested that higher frequencies of clicks produced faster rates of subjective time, although Penton-Voak et al., in a study using fewer conditions, found no such frequency effect. Extrapolation of Treisman's results to the present work might suggest that response times would be reduced to a greater extent by 25-Hz than 5-Hz clicks but, as noted above, the opposite effect was obtained.

EXPERIMENT 3

Experiments 1 and 2 showed that presenting click trains, a manipulation that increases duration estimates and thus presumably increased the rate of passage of subjective time, also made responses more rapid when response time was an important dimension of the cognitive task, on both single and choice reaction-time tasks (Experiment 1a) and on a mental arithmetic task (Experiment 2a). In contrast, the white noise had no significant effect on either reaction time (Experiment 1b) or the speed with which arithmetic could be performed (Experiment 2b). The contrast between these two experiments suggests a clear link between changes in the rate of subjective time and changes in the speed with which responses can be generated on tasks that do not explicitly involve time judgements: When subjective time is "speeded up", responses can be made more quickly than when it is not. It appears, therefore, that a key element in speeding up responses in our study is the change in the rate of subjective time, rather than some other possibilities such as cueing of the occurrence of the reaction time or arithmetic trial, or the mere presence of some auditory stimulus before the trial is presented. However, the exact mechanism by which the clicks exert their effects is discussed further later.

In Experiments 1 and 2 the critical measure of performance was the speed at which the response could be emitted, although the latencies of response were very different in the reaction time task and the arithmetic one, with much longer latencies in the latter case, suggesting that the effect was almost certainly not just dependent on motor speed. However, if subjective time is "speeded up", and this speeding-up effect changes information processing, the effect should be demonstrable in tasks that do not employ response speed as the critical performance measure, and Experiments 3 and 4 use two of these.

The rationale for both experiments is straightforward: Previous data suggest that click trains speed up the internal clock, making external events appear to last longer—that is, some clock time, t, seems to lengthen subjectively after clicks. The obvious question is whether it is possible to encode more information in some objective time period t when the internal clock is running faster, and the amount of subjective time elapsed is increased. Put simply, can people encode more information in a display that is presented for some time t when the display is preceded by a click train and thus putatively subjectively lengthened? Experiments 3 and 4 attempted to address this question by using variants of two classic experiments of cognitive psychology, Sperling's (1960) iconic memory task and Loftus, Johnson, and Shimamura's (1985) iconic masking task.

In 1960 Sperling published one of the most famous papers in the history of cognitive psychology. His participants were presented with matrices of letters (for brief periods of time ranging from 5–500 ms), where the letters were arranged in three rows, and then were subsequently tested on recall of the letters in the matrix. This procedure tested the amount of information available in a type of extremely short-term memory (later known as *iconic* memory). In different conditions, Sperling either asked for a *full* report, where participants simply had to recall as many letters as possible from the matrix, or a *partial* report where they only had to report from a sample of the array, where the appropriate sample was cued by an auditory stimulus. In the full report condition, people reported 4.5 letters on average. Sperling called this the "immediate memory span". In the partial report, people were cued to report from a particular row of the matrix. They recalled 3.3 letters on average from any given row and therefore Sperling argued that, at the time of the cue, people actually had an average of 9.9 (3×3.3) letters available, but the stored visual image decayed rapidly with time (at a rate of about 3 items per 50 ms).

Experiment 3 investigated the effect of preceding Sperling's (1960) iconic memory display material with click trains. In principle, the click trains will increase the speed of the internal clock pacemaker, so that the subjective period for which the matrices are presented should seem longer to the participant. If the participant experiences the matrix for longer, she or he may be able to extract more information on trials where the pacemaker is sped up than on trials without the click manipulation. Penton-Voak et al. (1996) found that the click trains could increase the pacemaker speed by an average of 10%. Sperling claimed that for periods of 5–500 ms, the presentation duration of the matrix made no difference to participants' recall. If the clicks increase the rate of passage of subjective time by the same amount as in Penton-Voak et al. (1996), then matrices presented for up to 400 ms will be unaffected by the click train manipulation even if one expects an increase of processing time of up to 20%. For example, a matrix presented for 300 ms would be subjectively experienced for 360 ms, so, if Sperling was right, no difference should be observed. In Experiment 3, participants viewed matrices for both 300 and 500 ms. The latter value exceeds Sperling's time criterion, and the click trains might therefore be expected to produce an effect. At subjective durations greater than 500 ms the task ceases to be an iconic memory task and starts to becomes a "normal" working/visual memory task, so one would expect recall to begin increasing towards the classic 7 ± 2 items (Miller, 1956). The matrix presentations were preceded either by 5 s of clicks or by 5 s without clicks, and participants were required to give a full report for each matrix viewed.

Method

Participants

A total of 20 University of Manchester undergraduates participated in exchange for course credit, which was not contingent on performance.

Design

Each participant received 64 trials split in to four different conditions: a matrix presented for 300 ms preceded by clicks, a matrix presented for 300 ms preceded by no clicks, a matrix presented for 500 ms preceded by clicks, and a matrix presented for 500 ms preceded by no clicks. Each condition was in force for 16 trials, and trials were presented in random order.

Apparatus and materials

The experiment was conducted in a small cubicle, insulated from external lights and noise. Participants were seated in front of the computer at a distance of 50 cm. The experimental program was written in E-Prime. All auditory stimuli were produced by the computer's internal speaker. The matrices presented were 3 × 4 arrays of white letters in font size 18 on a black background.

Procedure

Participants were instructed to look at a fixation cross (white on a black background) that appeared in the centre of the screen and to press the space bar on the keyboard when ready to commence each trial. This initiated a tone (700 Hz, 25 ms in duration) followed by either 5 s of clicks at a frequency of 5 Hz or 5 s without clicks, with the clicks arranged as in the previous experiments. The end of the 5 s was marked by another tone (700 Hz, 25 ms in duration), which cued the start of the presentation of the matrix. Each matrix was displayed for either 300 or 500 ms. At the end of the presentation period, a box appeared on the screen with space for participants to type as many letters as they could recall using the computer's keyboard and they were then required to press the "enter" key. A spacebar press was then prompted to initiate the next trial. Each participant experienced 64 trials, 16 in each condition.

Results and discussion

The mean number of correctly recalled letters for each of the four conditions—clicks 300 ms, silence 300 ms, clicks 500 ms, and silence 500 ms—are plotted in the upper panel of Figure 3. Inspection of data in the upper panel suggests an increase in the mean number of letters recalled in the click conditions compared to the no-click conditions for both display durations. These increases were 3.25% in the 300-ms condition and of 5.85% in the 500-ms condition. Inspection of Figure 3 also suggests that more letters were recalled when the matrix was displayed for 500 ms than when it was displayed for 300 ms regardless of whether matrix presentation was preceded by clicks or silence. These suggestions were confirmed by statistical analysis. A repeated measures ANOVA used condition (clicks or no clicks) and duration of matrix presentation (300 or 500 ms) as within-subject factors. There was a significant effect of clicks, $F(1, 19) = 4.59$, $p < .05$, so more letters were recalled when the matrix was preceded by clicks than for a period without clicks. There was also a significant effect of duration of matrix presentation, $F(1, 19) = 26.37$, $p < .05$, so significantly more letters were recalled when the matrix was displayed for 500 ms than when it was displayed for 300 ms. There was no interaction between the presence or absence of clicks and presentation duration, $F(1, 19) = 0.51$, $p = .48$, indicating that the clicks had a similar effect at both durations of matrix exposure.

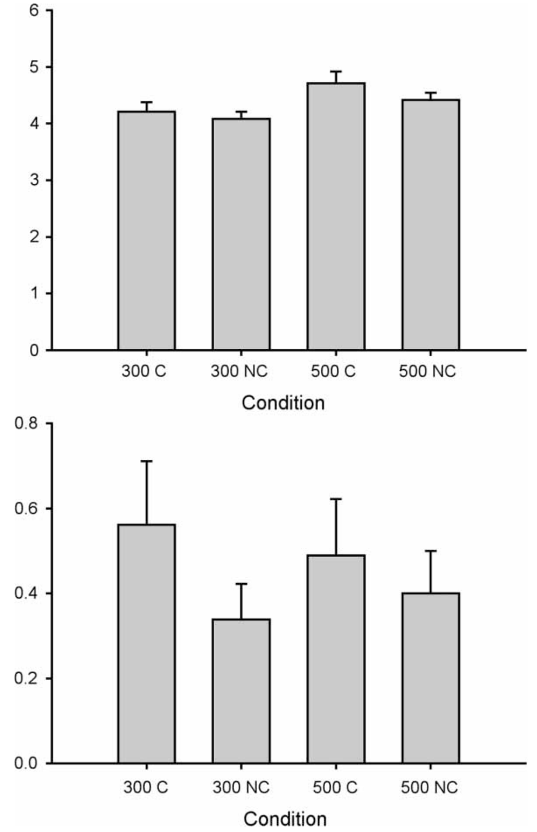

Figure 3. *Upper panel: Mean number of items correctly recalled in Experiment 3 plotted against condition: 300-ms exposure with clicks (300 C); 300-ms exposure no clicks (300 NC); 500-ms exposure with clicks (500 C); 500-ms exposure no clicks (500 NC). Vertical bars show standard errors of the mean. Lower panel: mean number of "false alarms" (i.e., items recalled that were not presented) from Experiment 3. Other details as for the upper panel.*

The next result of interest was the number of letters recalled that were not in the matrix—that is, the false-alarm rate—and mean values are shown in the lower panel of Figure 3. Inspection of the data suggests that the mean number of erroneous responses was higher in trials that were preceded by clicks (0.56 for displays of 300 ms, and 0.49 for displays of 500 ms) than for trials that were not preceded by clicks (0.36 for displays of 300 ms, and 0.40 for displays of 500 ms), and there appears to be small effect of display time on error rate. A repeated measure ANOVA conducted on the number of errors used condition (clicks or no clicks) and duration (300 or 500 ms) as within-subject factors. There was a significant effect of clicks versus no clicks, $F(1, 19) = 5.14$, $p < .05$, indicating that there were more false alarms produced when the matrix was preceded by clicks than when it was preceded by silence, but there was no effect of matrix duration on errors, $F(1, 19) = 0.039$, $p = .846$.

In order to examine the false-alarm rate, the ratio of the number of incorrect letters to correct letters recalled was calculated for each of the four conditions (error/correct). These ratios remained roughly constant for each condition taking values of .13 (clicks 300 ms), .09 (silence 300 ms), .10 (clicks 500 ms), and .09 (silence 500 ms) indicating that although the absolute number of incorrect responses increased following click trials, the number of errors remained roughly proportional to the number of correct responses made.

The results from Experiment 3 can be simply summarized. First, participants recalled more letters correctly from matrices that were preceded by clicks than from those that were not. Secondly, there were more false alarms made on trials that were preceded by clicks. The number of such errors decreased slightly for the longer display duration but this effect did not reach statistical significance. Thirdly, the duration of display presentation affected the number of correct responses made with more correct letters recalled following displays of 500 ms than following displays lasting 300 ms.

The present study found that participants correctly recalled significantly more letters following display durations of 500 ms than following displays lasting 300 ms (with a mean difference of 0.76 of a letter). This result was somewhat unexpected since Sperling (1960) failed to find any significant differences in performance at different exposure durations. One possible explanation is that, with longer exposure to the matrix, the participants had more time to extract information than at shorter exposure durations and thus were able to recall more letters. However, there is a marked discrepancy between the increase in physical exposure time (from 300 to 500 ms, an increase of 66%) and the increase in the proportion of letters recalled at (500 ms), which was only 8.52% for click trials and 8.18% for no click trials. Penton-Voak et al. (1996) estimated that the click trains they used increase subjective duration by an average of 10%, so we can expect a similar effect here. Given that the increase in physical duration from 300 to 500 ms had only a small effect on the number of letters recalled, the much smaller changes in subjective time might be expected to have a negligible effect, if their only mechanism of action was an increase in the subjective length of the letter display,[1] and this suggests that the clicks effects may do something else, or something else as well as changing the subjective duration of the displays. Additionally the increase in false-alarm rate in the clicks condition suggests that the effects on number of correct responses may be at least partly mediated by a shift of criterion, so people are producing more letters, whether correct or not. We return below to the question of just what that underlying psychological mechanism of the clicks effects might be.

Having shown in Experiment 3 that click trains can seemingly increase the subjective duration of a simple letter matrix display, and thus allow more information to be extracted from it for a given display time, we sought to examine this effect further. One question is whether this effect would generalize to memory for more complicated visual stimuli. Experiment 4 was designed to address this question by testing recognition memory for pictures.

EXPERIMENT 4

The task designed by Loftus et al. (1985) was intended to explore the “worth of an icon”, in other words to discover how much longer a stimulus has to be presented for in order to counter the effect (on a subsequent recognition task) of the iconic memory being destroyed by a visual mask. In the Loftus et al. task participants were presented with 36 photographs of landscapes, seascapes, and cityscapes, each briefly displayed for between 62 and 1,300 ms. After the picture (depending on condition) a visual mask (black and white noise field) was presented immediately (immediate mask), or after a delay of 300 ms filled with darkness (delayed mask), or no mask was presented at all (no mask). The participants were then given a yes/no recognition task with the 36 presented photographs mixed with 36 distractors that had not previously been presented. This procedure was then repeated for each participant with a new set of stimuli. Their results showed that an icon is “worth” around an extra 100 ms of processing time in order to reach the same level of recognition without a mask. The rationale for using this task in our current study is clear. If we precede the stimulus with click trains we should be able to reduce or eliminate the drop in recognition rate produced by the presence of a visual mask.

The primary hypothesis was that there would be a significant increase in the number of correctly recognized pictures in a recognition task when pictures that are followed by a mask are preceded by clicks on original presentation. The secondary hypothesis was that significantly more pictures would be correctly recognized generally, across all the levels of mask condition, when preceded by clicks on original presentation. Thirdly, in accordance with results from Loftus et al. (1985), recognition rate should be highest in the no-mask condition, lower in the delayed-mask condition, and lowest in the immediate-mask condition. For all participants in our study, pictures were presented for 200 ms and were preceded by click trains or silence. In different groups, the presentations were followed by an immediate-mask, delayed-mask, or no-mask display. The pictures were then intermingled with an equal number of distractors in a subsequent recognition test, and participants were required to judge whether or not the picture had been previously viewed.

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[1] We have unpublished data collected in our laboratory showing that people do indeed estimate the duration of a Sperling display as longer when the display is preceded by click trains.

Method

Participants

A total of 47 University of Manchester undergraduates participated in exchange for course credit, which was not contingent on performance.

Apparatus and materials

The apparatus was identical to that used in Experiment 1. The visual stimuli consisted of 160 neutral pictures (1,280 × 1,024 pixels) taken from the International Affective Picture series (Lang & Öhman. 1988), all previously rated for arousal and valence (Lang & Bradley, 1994), including affectively neutral scenes such as cityscapes, landscapes, nature scenes, animals, and people, which were presented during the experiment. A visual noise mask consisting of randomly arranged black and white dots displayed on a computer screen was used for the different levels of the mask condition.

Procedure

Each participant was randomly assigned to one of these three mask conditions (immediate mask, delayed mask, or no mask), so the mask condition was a between-subjects variable, and all participants received stimulus presentations preceded by clicks or without clicks. The dependent variable was the percentage of correctly recognized pictures identified in the test phase of the experiment.

Experimental sessions consisted of a study phase followed by a test phase. For each of the three levels of the mask condition 80 pictures were presented during the study phase, a random 40 of which were preceded by a 5-Hz click train lasting for 5 s, and the remaining 40 preceded by no clicks for 5 s. The arrangements for the click and no-click conditions were identical to those in previous experiments in the present article. Each picture was presented for 200 ms, followed by a 300-ms mask for the immediate-mask condition, a black screen for 300 ms, then a 300-ms mask for the delayed-mask condition, and just a black screen for the no-mask condition, in accordance with Loftus et al.'s (1985) procedure. There was then an 8-s intertrial interval before the beginning of the next trial.

Following the study phase, the test phase consisted of a yes/no recognition task. A total of 160 pictures were presented, 80 from the study phase and 80 previously unseen pictures, all displayed one by one in a random order. Participants responded to each picture using the computer keyboard, pressing "y" for yes or "n" for no in deciding whether the presented picture was one they had seen previously in the study phase of the experiment.

Results and discussion

Figure 4 shows the mean percentage accuracy of recognition across the three levels of mask condition (immediate, delayed, and no mask) and as a function of clicks versus no clicks. Inspection of the results in Figure 4 suggests two main findings: First, recognition rate was higher for stimuli preceded by clicks than for those preceded by no clicks in all three mask conditions; secondly the recognition rates across the mask conditions showed the same pattern of increase from none, delayed, and immediate as would expected from Loftus et al. (1985). Both these suggestions were supported by the statistical analyses.

A 3 × 2 mixed-design ANOVA was conducted in order to assess the effects of the type

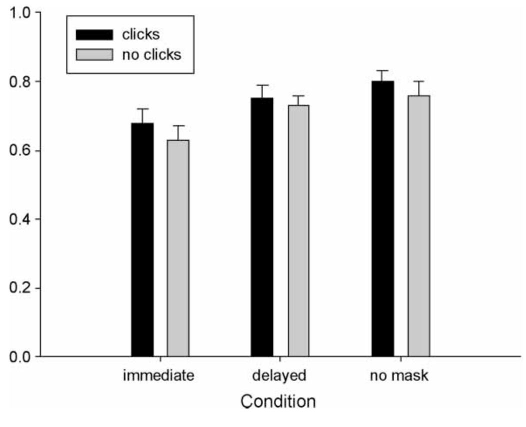

Figure 4. *Mean proportion of pictures correctly recognized plotted against condition (immediate, delayed, and no mask), for the click and no click conditions of Experiment 3.*

of a noise mask (immediate; delayed; no mask) as the between-subjects variable and the presence or absence of clicks (clicks/no clicks) as a within-subjects variable on the percentage accuracy of recognition. There was a significant main effect of mask level on recognition, $F(2, 44) = 3.76$, $p < .05$, so participants had significantly lower recognition rates in conditions where the noise mask was presented. There was also a significant main effect of clicks on the level of recognition, $F(1, 44) = 4.23$, $p < .05$, so participants showed higher recognition rates for stimuli preceded by clicks. There was no significant interaction between level of noise mask and level of clicks, $F(2, 44) = 0.24$, $p = .79$, which suggests that the click trains had the same effect on recognition rate regardless of which mask condition was employed.

The results clearly show that participants correctly recognized pictures that had been preceded by click trains more often than those that were preceded by silence. This suggests that, as in Experiment 3, the subjective duration of the presented display was increased when preceded by clicks as this speeds up the internal clock, and in turn the picture was more deeply encoded or more information/key features processed, leading to higher recognition rates. Additionally this effect was found across all three mask types, which in turn showed the expected pattern of increase in recognition rates from no mask, immediate mask, and delayed mask.

GENERAL DISCUSSION

Taken together, the results of all four of our experiments suggest an effect of the click train manipulation, shown to increase the rate of subjective time in a number of previous studies (e.g., Penton-Voak et al., 1996; Wearden et al., 1998, 2007), on the rate or efficiency of information processing during tasks that do not themselves require time judgements. In Experiments 1 and 2, click trains reduced the time needed to make responses in tasks involving reaction time or mental arithmetic, even though the response time for the latter task was three to five times longer than that for the former one. The results of Experiments 1 and 2 suggest that responses really can be "speeded up" by the clicks—that is, people can perform faster than without clicks, even though they are instructed to respond as fast as possible in all conditions. However, results of Experiments 3 and 4 show that the effect of the clicks is not merely to speed response times, but apparently to increase the quantity of information that can be extracted from a visual display. It should be noted that the performance measures in Experiments 3 and 4 involve the number of items correctly recalled or recognized, rather than response time, so increases in memory performance in these cases are not due to speeding of responses.

If we consider that subjective time and information processing are perhaps linked, there are at least three subtly different theoretical possibilities. One is that the change in the rate of subjective time is primary and by itself results in changes in performance on other measures, as the participants have "more time" to make their responses or process the events of the task, so rates of information processing or other measures of performance efficiency improve. The second is the reverse of the first: The clicks increase information-processing speed or efficiency directly, and this not only changes performance on nontiming tasks, but also increases the rate of subjective time as a secondary consequence. The third possibility is that some factor affects both the rate/efficiency of information processing and the rate of subjective time. Our data do not allow these three to be conclusively distinguished at present, but we discuss some potential mechanisms for the click trains effect later.

A small number of previous articles have reported effects of repetitive stimulation on tasks other than those requiring duration judgements, and two of these (Burle & Bonnet, 1999; Treisman, Faulkner, & Naish, 1992) used click trains, although the focus of interest of both studies was on the idea that specific frequencies of stimulation had different effects on performance, rather than on click/no click comparisons, as in our work. Both studies investigated the effect of different click frequencies on the time taken to make motor responses. Treisman et al.'s Experiment 1 and Burle and Bonnet's study were similar in that both used click trains to examine choice responses. In Treisman et al.'s case people had to press one key if a stimulus was on the right of a computer screen and another key if it was on the left. Burle and Bonnet used a task similar to that employed by Simon and Small (1969). Here, responses to a green or red stimulus had to be made with different hands, and trials were either "congruent" (when the stimulus appeared on the same side as the correct hand) or "incongruent" (where the stimulus was on the opposite side). Both studies presented click trains during the stimulus presentation, and in Burle and Bonnet's case the click trains started around 0.5 s before the stimulus. Treisman et al. used click frequencies ranging from 2.5 to 27.5 Hz in different conditions, and Burle and Bonnet used values from 19.5 to 22 Hz, with in both cases frequencies changing in 0.5-Hz steps. Treisman et al. did not use a "no click" condition, and, likewise, although pretraining including a condition without click trains was used in their study, Burle and Bonnet only reported data from conditions with click trains.

The main focus of the analysis of both studies was on the response time residuals remaining when mean response time was regressed against click frequency, and both studies found that different click frequencies appeared to have different effects. For example, in Burle and Bonnet's (1999) study a 20.5-Hz frequency increased response times, but frequencies of 21 and 21.5 Hz decreased them, relative to the value predicted from the regression line. This pattern is exactly that expected if the clicks were driving an internal pacemaker with an underlying frequency of around 21 Hz, or some multiple of 21 Hz. Treisman et al.'s (1992) work produced a complex pattern of results that cannot be easily summarized, but in general there was evidence for both increases and decreases in response times (relative to the regression predictions) with different frequencies. Neither study produced data that are simply comparable with ours, although in Burle and Bonnet's work higher click frequencies, even within the narrow range they used, made average response times shorter, which suggests that higher frequencies have more "powerful" effects, in contrast to the results of our Experiment 2.

In addition, effects of a different type of repetitive stimulation may have been prefigured in a slightly different literature. Wilkinson, Scholey, and Wesnes (2002) investigated the effects of chewing gum on performance on a battery of cognitive tests. They found that chewing sugar-free gum improved spatial and numeric working memory, and also immediate and delayed recall, compared with a no-chewing condition. Particularly interesting from our point of view were results from a "sham chewing" condition, where participants mimicked chewing movements, thereby generating their own repetitive stimulation. This manipulation decreased reaction times in a numerical working memory task (compared with no chewing), but increased simple reaction times. This work has given rise to a small literature, which is nevertheless large enough to contain contradictory results (e.g., contrast Stephens & Tunney, 2004, with Kohler, Pavy, & Van Den Heuvel, 2006) and different interpretations (see Scholey, 2004, for example), so the reliability and mechanism of action of gum chewing remains unresolved, but nevertheless the results may show some effect of repetitive stimulation on cognitive performance.

How does any sort of repetitive stimulation have an effect on cognitive performance? Potential answers remain highly speculative, but links between oscillatory activity of the brain, or certain brain rhythms, and cognitive performance have been discussed for many years. Burle, Macar, and Bonnet (2003) provide a review of many of the main ideas. The notion that the alpha rhythm (8–12 Hz) plays some role in information processing has a long history, with work by Surwillo (e.g., 1963) being prominent, and sometimes striking results are obtained. For example, Woodruff (1975) used biofeedback to either increase or decrease alpha frequency compared to baseline and found that increases in frequency decreased reaction times, and decreases in frequency increased them, relative to baseline conditions. This raises the possibility that our click trains are having some effect on alpha (although our frequencies are usually lower than the alpha frequency). Although links between alpha rhythm and aspects of information processing are sometimes found (Callaway & Yaeger, 1960; Lansin, 1957), other studies (Boddy, 1971; Treisman, 1984) have failed to obtain relations between alpha frequencies and either information processing or timing. More recent work has again suggested evidence of a link between alpha rhythms, information processing, and reaction time, although often by way of a complicated interaction of factors. For instance, Klimesch, Doppelmayr, Schimke, and Pachinger (1996) found that participants with high alpha frequency showed fast reaction times (RTs), whereas slow participants had low alpha frequency for similar results.

These recent findings by Klimesch et al. (1996) support the findings from earlier studies—for example, those of Varela, Toro, John, and Schwartz (1981). Varela et al. asked their participants to judge whether two briefly exposed visual stimuli with asynchronous onset appear as simultaneous or moving stimuli. They found that stimuli presented during negative polarity were perceived as simultaneous whereas those presented during positive polarity appeared moving. Further, Dustman and Beck (1965) found that RT to the onset of a light flash was fastest during the surface positive alpha cycle. In assuming that a visual stimulus is processed in the cortex after a delay (due to peripheral transmission time) of about 50 ms, the critical time window for the prediction of behavioural effects is not the phase of alpha at stimulation but that at the time of cortical processing, which is 50 ms post stimulus for the present example. Thus, if a stimulus is presented during the positive cycle, alpha will be at its negative cycle 50 ms later (assuming that alpha period is about 100 ms). Assuming that alpha is now in its excitatory phase, stimulus processing in the visual cortex will be enhanced, and RTs will decrease. When applying the same reasoning to the findings of Varela et al., Klimesch, Sauseng, and Hanslmayr (2007) concluded that stimuli presented during the positive cycle should coincide with enhanced stimulus processing in the brain, which in this case means that the two stimuli would not be perceived as one simultaneous stimulus but instead as two separate (moving) stimuli. Thus, there are reasons to assume that alpha phase controls cortical excitability.

The idea that information processing rate can be enhanced with increased alpha power was also shown by Klimesch, Sauseng, and Gerloff (2003) who artificially increased alpha power by means of repetitive transcranial magnetic stimulation at individual upper alpha frequency and found enhanced performance on a task of mental rotation. The full discussion of the alpha literature is beyond the scope of this article, but it is clear that a simple explanation of our results based on synchronization of alpha activity is problematical, since there is conflicting evidence as to the role of alpha in information processing, and the issue of what, if any, role it plays is yet to be fully resolved.

Another idea, also present in the literature for some years, has been that information processing is discontinuous, with information transmission between different parts of cognitive systems occurring in "packets" separated in time (see Dehaene, 1993, for example). According to this view, operations that increase the rate at which packets could be transmitted, possibly by driving underlying oscillatory processes, would increase the rate of information processing.

Burle et al. (2003) themselves present a potential mechanism for effects of repetitive stimulation, their *dual pacing* hypothesis. To simplify slightly, suppose two neurons, one downstream from the other, form a chain of information transmission. A problem is to transmit the neural firing through the chain efficiently in the presence of random background neural activity, which tends to obscure the transmitted signals. Burle et al. propose that repetitive stimulation has two effects. First, it synchronizes transmission in the upstream neuron, so spikes are grouped into "packets" distinct from random background activity. Secondly, it synchronizes the receptivity of the downstream neuron for the packets received from the upstream one, so that when these arrive the downstream neuron is in a maximally receptive phase and passes the signal on efficiently. If any kind of repetitive stimulation, from clicks and flashes, to chewing, does have the ability to synchronize neural activity, then Burle et al.'s hypothesis provides a potential mechanism for its action.

In conclusion, our results show that repetitive stimulation, which has previously been shown in many studies to increase the rate of subjective time, can apparently increase the rate of information processing, or other aspects of performance efficiency, over and above that possible without the stimulation. In contrast, a white noise manipulation has no effect on response times. We acknowledge that our results may raise more questions than they answer, about parameters of the experimental conditions needed to produce the effects found, their scope, and underlying mechanisms by which the effects are obtained, and they represent a point of departure for the study of relations between subjective time and aspects of nontemporal information processing, rather than an end point where all issues are resolved. Nevertheless, our results suggest deep connections between the perception of duration and many other aspects of cognitive processing, which may lead to a greater understanding of both processes.

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