Temporal Difference Thresholds and Repetitive Stimulation:

Can Click Trains Improve Temporal Sensitivity?

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Abstract

Trains of auditory clicks increase subsequent judgements of stimulus duration by approximately 10%. Scalar timing theory suggests this is due to a 10% increase in pacemaker rate, a main component of the internal clock. The effect has been demonstrated in many timing tasks, including verbal estimation, temporal generalisation, and temporal bisection. However, the effect of click trains has yet to be examined on temporal sensitivity, commonly measured by temporal difference thresholds. We sought to investigate this both experimentally; where we found no significant increase in temporal sensitivity, and computationally; by modelling the temporal difference threshold task according to scalar timing theory. Our experimental null result presented three possibilities which we investigated by simulating a 10% increase in pacemaker rate in a newly-created scalar timing theory model of thresholds. We found that a 10% increase in pacemaker rate led to a significant improvement in temporal sensitivity in only 8.66% of 10,000 simulations. When a 74% increase in pacemaker rate was modelled to simulate the filled-duration illusion, temporal sensitivity was significantly improved in 55.36% of simulations. Therefore, scalar timing theory does predict improved temporal sensitivity for a faster pacemaker, but the effect of click trains (a supposed 10% increase) appears to be too small to be reliably found in the temporal difference threshold task.

Keywords: Click train; temporal sensitivity; threshold, scalar timing theory, pacemaker.

Introduction

Scalar timing theory suggests that human interval timing is underpinned by a pacemaker-accumulator type internal clock (Gibbon, 1977; Gibbon & Church, 1984; Gibbon, Church, & Meck, 1984). The pacemaker is said to emit pulses at a given rate, which are sent to an accumulator in working memory via an attentional switch. The number of pulses accumulated during a certain interval forms the basis for temporal judgements, and subsequent memory and decision-making processes are also implicated, depending on the task.

It appears that the rate of this pacemaker can be altered in a number of ways. Treisman, Faulkner, Naish, and Brogan (1990) presented trains of auditory clicks alongside visual stimuli to be timed, and participants assigned verbal labels to the duration of the visual stimuli (e.g. '2 seconds'). Accompanying the stimuli with click trains significantly increased estimates of their duration, compared to when there was no concurrent click trains. The authors argued that the train of clicks increased participants' arousal, which in turn increased the rate of the pacemaker.

Penton-Voak, Edwards, Percival, and Wearden (1996) presented click trains *before* auditory and visual stimuli and found this similarly increased duration estimates. Furthermore, estimates increased as a proportion of stimulus duration. In other words, longer stimulus durations were subject to greater (relative) overestimation, known as a multiplicative effect. This was confirmed by regressing each participant's estimates against the stimulus durations. The resulting slope coefficient for estimates following click trains was significantly greater than when a period of silence preceded the stimuli. Penton-Voak et al. (1996) argued that the repetitive auditory stimulation increased the rate of the pacemaker by around 10%. This approximate increase in pacemaker rate has been confirmed in subsequent research (Wearden, Edwards, Fakhri, & Percival, 1998;

Wearden, Norton, Martin, & Montford-Bebb, 2007), and is generally inferred from the slope difference in verbal estimation.

It should be noted that the train of repetitive stimulation need not be auditory in order to increase duration estimates. Visual flickers (commonly presented as flashing shapes onscreen) have a similar effect on perceived duration, whether presented before the stimuli to be timed (Droit-Volet & Wearden, 2002; Wearden, Williams, & Jones, 2017) or as that stimulus (Herbst, Chaumon, Penney, & Busch, 2015; Herbst, Javadi, van der Meer, & Busch, 2013; Ortega & Lopez, 2008; Treisman & Brogan, 1992). However, recent work has found that trains of tactile stimuli, presented via a bone conductor to the fingertip, does not multiplicatively increase estimates (Jones & Ogden, 2016). Instead, estimates following the tactile trains increased additively, indicative of an attentional effect often attributed to the switch of the internal clock. Previous research has tended to use click trains rather than visual flickers as click trains are easier to control in terms of their presentation to participants. We will therefore limit our current investigation to the effect of repetitive auditory stimulation.

Apparent changes in pacemaker rate are not limited to the effect of repetitive stimulation. Duration estimates for visual intervals are multiplicatively shorter than those for auditory intervals (Goldstone & Lhamon, 1974; Jones, Poliakoff, & Wells, 2009; Wearden et al., 1998; Wearden, Todd, & Jones, 2006), an effect we will refer to as the *modality difference*. In addition, empty intervals (i.e. a period of silence bounded by two beeps) are estimated as multiplicatively shorter than filled intervals (e.g. a continuous tone; Wearden et al., 2007), known as the filled-duration illusion. In fact, these two effects have been known to lead to greater effect sizes than click trains; when comparing similar procedures across papers, slopes co-efficients for auditory intervals appear to be on average 1.20 times larger than the slopes co-efficients for visual intervals, while slopes

for filled intervals appear to be on average 1.74 times those for empty intervals¹. The authors interpreted these slope differences as differences in pacemaker rate (Wearden et al., 1998; Wearden et al., 2007; Jones et al., 2009), which we will here quantify as the pacemaker appearing to run 20% faster for auditory than visual stimuli, and 74% faster for filled than empty stimuli. Clearly, these effects are greater than the suggested 10% increase for click trains, as compared to a period of silence preceding the stimuli.

Furthermore, apparent changes in pacemaker rate are not exclusive to the verbal estimation task. Other common tasks that have been used to investigate changes in pacemaker rate include temporal generalisation (where participants judge whether presented durations are the same as a standard duration) and temporal bisection (where participants judge whether durations are more similar to a ‘short’ standard duration or a ‘long’ standard duration). In each task, there appears to be superior performance for filled auditory intervals when compared to empty auditory intervals or filled visual intervals, consistent with suggested pacemaker rate effects. **Table 1** provides an overview of the research conducted that employs these tasks to investigate the aforementioned effects on pacemaker rate.

¹ See section A of the supplementary material for details of these slope factor calculations.

Table 1. Overview of modality difference, filled-duration illusion, and click train experiments which have utilised verbal estimation, temporal generalisation, temporal bisection, and temporal difference threshold tasks.

Task	Temporal Effect or Illusion		
	Modality Difference	Filled-Duration Illusion	Click Trains
Verbal Estimation	Jones et al. (2009)	Wearden et al. (2007)	Penton-Voak et al. (1996)
	Wearden et al. (1998)	Wearden et al. (2007)	Treisman et al. (1990)
	Wearden et al. (2006)		Wearden et al. (1998)
			Wearden et al. (2007)
Temporal Generalisation	Jones et al. (2009)	Wearden et al. (2007)	Penton-Voak et al. (1996)
	Klapproth (2002)		
	Wearden et al. (1998)		
Temporal Bisection	Droit-Volet, Tourret, & Wearden (2004)	Droit-Volet (2008)	Droit-Volet (2010)
	Penney, Allan, Meck, & Gibbon (1998)		
	Penney, Gibbon, & Meck (2000)		
	Wearden, et al. (2006)		
Temporal Difference Threshold	Buffardi (1971)	Buffardi (1971)	
	Grondin (1993)	Grondin (1993)	
	Grondin, Meilleur-Wells, Oulette, & Macar (1998)	Grondin et al. (1998)	
	Jones et al. (2009)	Rammsayer (2010)	
	Marks (1987)	Rammsayer & Lima (1991)	
	Ulrich, Nitschke, & Rammsayer (2006)		

It is clear from **Table 1** that the effect of click trains has yet to be investigated on another common timing task; temporal difference thresholds (also ‘duration discrimination’). Temporal sensitivity is often measured using a staircase procedure, where participants judge which of two durations is longer, with their decision affecting the difficulty of the next trial. This procedure calculates the smallest difference that

participants can discriminate between two durations, typically 75% of the time, relative to a particular standard duration. Despite differences in procedural or calculation conventions, there is a relatively clear picture that thresholds for auditory stimuli are significantly lower than those for visual stimuli (e.g. Grondin, 1993), and similarly, thresholds for filled stimuli are significantly lower than those for empty stimuli (e.g. Rammsayer, 2010). The same superior performance for certain conditions in the three aforementioned tasks therefore persists in the temporal difference threshold task. This had led some authors to argue that the same increase in putative pacemaker rate that results in multiplicatively higher estimates in the verbal estimation task would lead to lower temporal difference thresholds (Jones et al., 2009). That is, under the assumptions that (i) click trains increase pacemaker rate, and (ii) pacemaker rate is responsible for the changes in performance across the four tasks, a faster pacemaker should improve the ability to perceive a difference between two durations, thus improving temporal sensitivity.

On the other hand, it could be argued that the pacemaker explanation was applied to the temporal difference threshold task without due consideration of the complex mathematical properties of the *scalar* pacemaker. It is often argued that a faster (Poisson) pacemaker leads to more accurate judgements of duration (Rammsayer, 2008; Rammsayer & Grondin, 2000; Troche & Rammsayer, 2011). However, the pacemaker of scalar timing theory has a unique specification in order to obey the scalar property, which will be discussed in a later section. In addition, the temporal difference threshold task has not yet been modelled according to scalar timing theory (unlike verbal estimation, Wearden, 2015; temporal generalisation, Wearden, 1992; and temporal bisection, Wearden, 1991b). It is therefore not clear at present whether the specification of the scalar pacemaker will mask any benefits of increased pacemaker rate. It may be the case that

any increase in the rate of the scalar pacemaker is mathematically cancelled out elsewhere in the process/timing system. For example, though increasing the rate of the pacemaker by 10% may increase the perceived difference in duration between the two stimuli by 10%, this may not necessarily translate into a 10% improvement in temporal sensitivity.

In summary, the as yet unanswered question is whether click trains can increase temporal sensitivity, as measured by a reduction in temporal difference thresholds. Click trains are known to increase verbal estimates by approximately 10%, and other effects on estimates (such as the modality difference and the filled-duration illusion) have been found to likewise affect temporal difference thresholds, presenting the same pattern of conditions across tasks. It would therefore be logically consistent for click trains to improve temporal sensitivity. Our investigation to answer this question forms a two-pronged approach. First, we will test empirically whether click trains significantly reduce temporal difference thresholds. Second, we will find our participants' best-fitting parameters (including pacemaker rate and internal decision threshold), and simulate the effect of a 10% increase in pacemaker rate on their temporal difference thresholds. We will run 10,000 of these simulations in order to approximate the proportion of the time where click trains lead to significant reductions in thresholds. We will compare these findings to a simulated increase of 74% to emulate the filled-duration illusion, in order to allow for a magnitude comparison, and to test the validity of the model. The simulations will also allow deeper insight into the actual predictions of the scalar timing model and the assumed effect at several stages of the task, which will not be granted by our empirical investigation alone.

Empirical Investigation of the Effect of Click Trains
on Temporal Difference Thresholds

144 Method

145 *Participants*

146 Ninety-two undergraduate psychology students from the University of Manchester
147 participated in exchange for course credits. All participants gave informed written
148 consent, and the study was approved by the University of Manchester Research Ethics
149 Committee (ref: 14344).

150 *Apparatus*

151 A Dell computer was used to deliver the experiment, which was programmed using E-
152 Prime (Psychology Software Tools Inc.). Two speakers produced the auditory stimuli.
153 Responses were typed using the numeric keypad of a standard keyboard.

154 *Procedure*

155 Participants completed a 50-trial temporal difference threshold task² under three
156 conditions in a random order. In each condition, trials were preceded by 5 second pre-
157 stimulus events: 5 Hz click trains, white noise, or silence. In order to ensure participants
158 were not differentially cued to the oncoming stimulus in the different conditions, each
159 event was bounded by two 25 ms 700 Hz ‘beeps’. Following the second beep, a 500 ms
160 delay preceded the 500 Hz standard and comparison tones.

161 The standard duration was 1000 ms, while the comparison duration began at 700
162 ms. After each trial, participants were asked to press ‘1’ if they judged the first tone to be
163 longer or ‘2’ if they judged the second tone to be longer. If participants responded

² The same threshold task without the pre-stimulus events has been used previously by Jones et al. (2007) and Williams et al. (2019) amongst others.

correctly, the difference in duration between the two tones was decreased, whereas if participants respond incorrectly the difference was increased. The order of the standard and comparison durations was randomised between trials.

Threshold procedures were controlled by the weighted up-down staircase method (Kaernbach, 1991), which allows the upward steps (S_{up}) and downward steps (S_{down}) to be of different sizes. Kaernbach (1991) stated the equilibrium point for X_p as $S_{up}p = S_{down}(1-p)$. In the current task, convergence to X_{75} was desired, which relates to the ability to correctly distinguish between durations (with a difference of X) 75% of the time. This necessitated a '3-up, 1-down' staircase, where the difference between the tones was decreased by one step size if participants were correct, and increased by three step sizes if participants were incorrect. The step size was initially set to 15 ms, but decreased to 10 ms after 30 trials in order to find the threshold more precisely. Temporal difference thresholds were calculated from the mean difference between the two tones over the last 20 trials in each condition.

Results

The data from 17 participants were excluded due to either apparent misunderstanding of the task, inattention, or confusing the response buttons. This was identified as resulting temporal difference thresholds above 600 ms in any of the conditions. This criterion was selected *a priori* as it is twice the starting difference between the standard and comparator durations, as used in previous work (Williams, Yüksel, Stewart, & Jones, 2019). Therefore, the data of 75 participants from the original 92 were analysed.

Figure 1 shows the mean difference between the standard and comparison durations across the 50 trials for the three pre-stimulus events (click trains, white noise,

188 and silence). Inspection of the figure suggests little or no difference between conditions.
189 See **Figure 2** for a confirmation of this pattern.

190
191 **Figure 1.** Mean difference between the standard and comparator across the 50 trials
192 following each pre-stimulus event. The vertical solid line separates the last 20 trials over
193 which the step size was reduced and the temporal difference thresholds were calculated.
194 Error bars display within-participant standard error (Morey, 2008), and are presented in
195 grey to increase visibility of the means.

196

Figure 2. RDI plot (Raw data, Descriptive statistics and Inferential tests) presenting the mean thresholds values following each pre-stimulus event. The mean for each condition is presented as the larger empty shapes, with error bars indicating standard error. Smaller filled shapes denote the threshold values for each participant in each condition. The distribution for each condition is mirrored to form an outline around each mean.

A one-way repeated measures ANOVA³ found no significant differences between temporal difference thresholds following the different pre-stimulus events, $F_{(2,148)} = 0.81$, $p = .449$, $\eta_p^2 = .011$. A Bayesian repeated measures ANOVA with default prior scales (Wagenmakers, et al., 2017; Jeffreys, 1961) calculated with JASP (JASP Team, 2017) found a Bayes factor of 10.706:1 in favour of the null hypothesis. A paired samples t-test was conducted to investigate the specific difference between thresholds following click trains and silence, and also found no significant difference, $t_{(74)} = 0.99$, $p = .326$, $BF_{01} = 4.92$, $d = 0.10$.

³ A Friedman test confirmed the validity of these results, given significant deviations of the residuals from normality (Shapiro-Wilks $p < .001$ for all conditions): $\chi^2(2) = 5.20$, $p = .074$. Similarly, a Wilcoxon Signed Ranks test found no significant difference between thresholds following clicks or silence, $Z = 0.19$, $p = .853$. Section B of the supplementary material reports similar results when no participants are excluded, and when excluding outliers defined as > 2.5 SD from the means in each condition.

211 Discussion

212 When temporal difference threshold trials were preceded by click trains, white noise, and
213 silence, no significant difference was found between the three conditions. The data
214 appeared to be almost 11 times more likely under the null hypothesis in this instance,
215 indicating strong evidence against the alternative hypothesis (i.e., that temporal
216 sensitivity judgements would be affected by the presence of click trains relative to white
217 noise and silence). When thresholds following click trains and silence were directly
218 compared, the Bayes factor in favour of the null reduced to 5 (moderate evidence), but
219 the difference remained non-significant. This is surprising, as it appeared to be logically
220 consistent (given the other effects and tasks) for click trains to significantly decrease
221 temporal difference thresholds.

222 Given this strong evidence in favour of the null hypothesis, there are three likely
223 possibilities concerning the effect of the pacemaker on temporal sensitivity. The first
224 suggests that the mathematics of scalar timing theory does not predict improvements in
225 temporal difference thresholds following an increase in pacemaker rate. A second
226 possibility suggests that an improvement in temporal difference thresholds is predicted
227 following an increase in pacemaker rate, but that a 10% increase is too small to be
228 detected over the noise in the system. Finally, the third possibility suggests that a 10%
229 increase in pacemaker rate would be reliably detected, but we encountered a Type II error
230 with our experimental results. See **Table 2** for further details of these possibilities, which
231 are dissociable by their predictions of the results of 10,000 simulations of a 10% increase,
232 and predictions following a 74% increase in pacemaker rate. In the table, a 10% increase
233 in pacemaker rate simulates the performance following click trains versus silence, while
234 a 74% increase simulates performance for filled versus empty intervals.

235

236 **Table 2.** The three likely possibilities following the experimental results.

Possibility	The inference in Experiment 1 was...	Why?	So will 10,000 simulations find different results?	So will simulating a 74% increase find different results?
1	Correct (True negative)	Scalar timing theory does not actually predict higher sensitivity from a faster pacemaker. Perhaps the increase in the number of pulses accumulated is cancelled out by another stage in the process. Applications of the pacemaker explanation to this task were naïve and there is a non-pacemaker explanation for modality differences and the filled-duration illusion in thresholds.	No - Only around 5% of the 10,000 simulations for a 10% increase will find a significant difference (chance)	No – Only around 5% of the 10,000 simulations for a 74% increase will find a significant difference (chance)
2	Correct (True negative)	Scalar timing theory does predict higher sensitivity from a faster pacemaker, but a 10% increase leads to an undetectable effect due to a high level of noise in the task, and will continue to be undetectable if repeated.	No – Only around 5% of the 10,000 simulations for a 10% increase will find a significant difference (chance)	Yes – More than 5% of the 10,000 simulations for a 74% increase will find a significant difference
3	Incorrect (False negative)	Scalar timing theory does predict higher sensitivity from a faster pacemaker, but we encountered a Type II error, and a repetition of a 10% increase is likely to find a significant difference.	Yes – More than 5% of the 10,000 simulations for a 10% increase will find a significant difference	Yes – More than 5% of the 10,000 simulations for a 74% increase will find a significant difference. This percentage will be greater than the percentage for a 10% increase

Computational Investigation of the Effect of Click Trains
on Temporal Difference Thresholds

Unlike verbal estimation, temporal generalisation and temporal bisection tasks, where performance has been modelled using the framework of scalar timing theory (Wearden, 2015, Wearden, 1992, and Wearden, 1991b respectively), the temporal difference threshold task has no published model. We were kindly given access to a model of the threshold task (Wearden, unpublished manuscript) which incorporates the basic computations of the task; for example calculating the next comparison duration contingent on performance. We have expanded this model to embody the specifications of scalar timing theory⁴. This section will report the main steps in this process, before reporting the modelling results.

The Pacemaker of Scalar Timing Theory and the Scalar Property

According to Gibbon and Church (1984), variance in the pacemaker “ought to follow the Poisson law” (p. 475). For those unfamiliar, the Poisson distribution controls the probability of the number of events occurring in a given time period, where events (or pulses) occur independently and continuously at a constant rate. For any Poisson distribution, the mean number of events occurring in that time period is equal to the variance around that mean. In addition, the time between events (or pulses) in a Poisson distribution is exponentially distributed; as Gibbon & Church (1984) state, “interpulse intervals are exponentially distributed in a steadily varying stream” (p. 475).

⁴ Where possible, our choice of parameters has been taken from Gibbon & Church (1984), and where other parameters have not been specified, we have made sensible and reasoned decisions. Rationales accompany our decisions in text, but a summary of these decisions can be found in Section C of the supplementary material.

The use of a Poisson pacemaker as a component of the internal clock is not an original idea (see Creelman, 1962 for example) but a purely Poisson process is often avoided by itself. Since the variance is equal to the mean, the standard deviation becomes a lower proportion of the mean with increasing stimulus duration, meaning greater relative accuracy with longer durations. However, real animal and human timing obeys the scalar property, where it is the standard deviation (not the variance) that is linearly related to the mean. In other words, the coefficient of variation (CV; sd/m) of timing judgements (and implicitly the CV of the number of pulses accumulated in a given time period) is relatively stable across stimulus durations.

There is therefore an additional mechanism in scalar timing theory to embody the scalar property. Gibbon and Church (1984) suggest that mean pacemaker rate drifts slightly from trial to trial, sampled from a normal distribution with an undisclosed CV, known as the drifting rate. That is, on each trial, the mean of the Poisson distribution (from which the number of pulses is sampled) is itself sampled from a normal distribution, with a given CV (drifting rate). As pacemaker rate increases, a lower drifting rate is needed to result in a constant CV, but the authors did not calculate these combinations of pacemaker rate and drifting rate that obey the scalar property. Therefore we needed to search for these scalar timing approved combinations before we began to fit participants' data with the model, to ensure that we are correctly embodying scalar timing theory.

A Search for Scalar Combinations of Pacemaker Rate and Drifting Rate

An important first stage in modelling a task under the assumptions of scalar timing theory is to ensure that combinations of the pacemaker rate and drifting rate result in a constant CV of the number of pulses accumulated across duration. Therefore our first task was to select a range of plausible pacemaker rates, and find the accompanying drifting rates that

result in a constant CV across duration. We selected 23 different pacemaker rates (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1500, 2000, 5000, 10000 pulses per second) as a compromise between casting a large net and the practical constraints of modelling. We investigated 11 drifting rates of 0 to 1, in steps of 0.1. A drifting rate of 0 means that the pacemaker rate does not drift from trial to trial (a pure Poisson pacemaker), while a drifting rate of 1 means that the pacemaker rate on each trial is sampled from a normal distribution where the standard deviation is equal to its mean. See section D of the supplementary material for further details of this procedure. Of the 253 possible combinations of pacemaker rate and drifting rate, 124 (49%) were found to lead to a constant CV (of the number of pulses accumulated) across stimulus durations, thus obeying the scalar property.

The Temporal Difference Threshold Model

Though the duration of the standard and comparison intervals is determined by the staircase procedure, the perception of these durations is additionally determined by the switch latency (See section E of the supplementary material for details). Following the adjustment of perceived duration due to the switch, the number of pulses accumulated during the perceived standard and comparison durations were then sampled from a Poisson distribution. The mean and variance of this distribution was the sampled pacemaker rate for that trial.

The decision rule used to determine whether the participant would be able to perceive a difference in duration is given in Equation 1, where N_S and N_C are the number of pulses accumulated during the standard and comparison intervals respectively, and b is the decision threshold, discussed in the next section.

$$\frac{|N_S - N_C|}{(N_S + N_C)/2} > b \quad (\text{Equation 1})$$

This means that the simulated participant can distinguish a difference if the absolute difference in pulses, divided by the average number of pulses, exceeds a certain proportionate value (the decision threshold). Equation 1 is reminiscent of Gibbon and Church's (1984) relative decision rule used in temporal generalisation (our Equation 2, their Equation 2b⁵).

$$\frac{|M_S - M_T|}{M_S} < b \quad (\text{Equation 2})$$

Here, M_S and M_T refer to the memory of the number of pulses accumulated in the standard duration and the current presented duration. In this task, the comparison is identified as the standard when the expression on the left is lower than the decision threshold. We decided to divide by the average number of pulses instead of just N_S for three reasons: (1) our standard duration is never labelled as such, (2) its position alternates on each trial, and (3) it is likely to be perceived as a different number of pulses on each trial. We therefore argue that it is reasonable to assume that participants may use the average number of pulses in the standard and comparison as a ruler by which to judge the difference between them, rather than the standard duration by itself.

This assumption is echoed by Wearden (2004) in his decision rule for episodic temporal generalisation (our Equation 3, his Equation 5). This is a variation of temporal generalisation with no standard duration. Similar to the threshold task, participants are presented with two tones on each trial, but they have to decide whether the durations are equal rather than which one is longer (See Wearden & Bray, 2001 for full procedural details). Therefore this variation requires no retrieval of a standard from reference

⁵ Equations 2 and 3 have been simplified slightly for readability, but the original meaning has been preserved.

memory, unlike in Gibbon & Church (1984) and Equation 2. Here, t_1 and t_2 refer to transformations of the two durations. Participants are thought to judge the durations to be the same when the expression on the left is below their decision threshold⁶.

$$\frac{|t_1 - t_2|}{(t_1 + t_2)/2} < b \quad (\text{Equation 3})$$

Returning to Equation 1, the expression on the left is equal to 0.35 at the start of the task, regardless of pacemaker rate, when the standard is 1,000 ms and the comparison is 700 ms. This means that at mean level, it would appear that an increase in pacemaker rate will not affect temporal difference thresholds, but an effect may be driven by the concurrent change in variability. On a given trial, if this proportion is greater than or equal to a participants' decision threshold, the participant can perceive a difference in the number of pulses in the standard and comparator. Note that this does not necessarily ensure a correct answer. It could be the case that a lower number of pulses was accumulated during the (longer) standard than in the comparison, due to the random nature of the inter-pulse intervals. However, if the proportion is lower than the decision threshold, the participant must guess, which has a 50% chance of success (See **Figure 3** for a decision flowchart).

⁶ Equation 1 includes a 'more than' comparison, while Equations 2 and 3 include 'less than' comparisons because Equation 1 (for the temporal difference threshold task) results in a judgement indicating whether the two durations are different, while Equations 2 and 3 (for temporal generalisation tasks) result in judgements indicating whether the comparison equals the standard or whether the two tones are equal.

Figure 3. Flowchart of decisions in the temporal difference threshold task.

As Gibbon and Church (1984) specify in their Appendix E, the decision threshold is sampled from a normal distribution on each trial, and we have parameterised a CV of 0.2. As in our experiment, the 3-up 1-down staircase procedure runs for 50 trials, with an initial step size of 15ms for the first 30 trials, which reduces to 10 ms for the remaining 20 trials. The difference threshold is calculated as the average difference between the standard and comparator over the last 20 trials.

Fitting Procedure

To find participants' best fitting pacemaker rate, drifting rate and decision threshold for their 'silence' condition, 10,000 simulations were conducted for each of the 124 pre-approved pacemaker-drifting rate combination, and 6 different decision thresholds, which varied from 0 to 0.35 in steps of 0.05⁷. This led to 744 possible combinations. For each

⁷ The inclusion of 0 as a possible decision threshold was the result of a programming error. We decided to keep this in for two reasons: (1) All fitted parameters are merely estimations of underlying values. Though the ability to always discriminate a difference is improbable, this may be the best available approximation.

participant, the difference between the standard and comparator over their last 20 trials was then compared to each of the possible combinations. The combination with the lowest mean absolute difference (MAD) across the last 20 trials was selected⁸. See section F of the supplementary material for best-fitting parameter values for each participant, and subsequent MAD values.

Simulating an Increase in Pacemaker Rate

Using the best fitting combination of pacemaker rate, drifting rate and decision threshold for each of the 75 participants, we modelled an increase in pacemaker rate of 10% (simulation of click trains compared to silence) and 74% (simulation of filled compared to empty intervals). We are primarily interested in whether these increases in pacemaker rate, and resulting differences in variability, result in significant improvements of temporal sensitivity (as measured by temporal difference threshold). However, we will also compare the number of ‘guesses’ and number of correct answers over the 50 trials in order to illuminate the effect of increased pacemaker rate on the inner mechanisms of the model (and participants’ assumed behaviour).

We will first simulate the difference in thresholds for filled versus empty intervals in order to test the validity of the model. This is because this effect (larger thresholds for empty compared to filled intervals) has already been found (Buffardi, 1971; Grondin, 1993; Grondin et al., 1998; Rammsayer, 2010; Rammsayer & Lima, 1991), and in published work at least, the effect has been found to be robust and reliable. We do not

(2) Since the decision threshold is sampled from a normal distribution minus any values below zero, the decision threshold on each trial is highly likely to be above zero.

⁸ We fitted the last 20 trials instead of the whole 50 trials because performance here is a large determiner of the resulting temporal difference threshold, since its value is equal to the average over these trials. If a combination simulates participants’ data well over these trials on average, it is likely that the resulting performance on each run will differ much less than if the fitting compared all 50 trials.

expect the model to predict a significant difference 100% of the time, however, we would expect this effect to occur in the majority of simulations.

Since the random sampling of the number of pulses and guess success largely determines performance over the 50 trials, the results garnered from one repetition are likely to be unreliable. We therefore ran 10,000 simulations for each increase in pacemaker rate. Paired samples t-tests were then conducted to compare the number of guesses, correct answers and resulting temporal difference thresholds for participants' fitted simulations and rate-increased simulations for each of the 10,000 simulations. This allows us to determine which of the three possibilities outlined in **Table 2** and discussed earlier is correct, following the strong to moderate evidence in favour of the data under the null hypothesis.

Modelling Results for a 74% Increase in Pacemaker Rate (Filled-Duration Illusion)

See **Figure 4** for the histograms of t -statistics, p -values and Cohen's d values for the comparisons on number of guesses, number of correct answers, and temporal difference thresholds for the simulated effect of filled versus empty intervals.

The number of guesses is an index of the number of times the proportion expressed in Equation 1 failed to exceed the decision threshold. The number of correct answers relates to the number of times the proportion expressed in Equation 1 exceeded the decision threshold, in addition to the number of successful guesses. Regardless of the reason, a high number of correct answers is the key to obtaining a low temporal difference threshold. **Table 3** contains the means and standard deviations of the distributions of t -statistics and Cohen's d values, in addition to the percentage of simulations that resulted in a significant difference for the three comparisons.

Table 3. Modelling results for a 74% increase in pacemaker rate across 10,000 simulations.

Comparison	t_m	t_{sd}	% _{sig}	% _{sig} F>E	% _{sig} E>F	d_m	d_{sd}
Total Guesses	4.82	0.99	99.72	0.00	99.72	0.27	0.06
Total Correct	-1.46	0.27	31.44	31.38	0.06	-0.14	0.11
Threshold	2.14	1.12	55.39	0.03	55.36	0.15	0.08

Note. t_m = mean t -statistic, where a positive t indicates a greater score for empty than filled intervals, t_{sd} = standard deviation of t -statistics, %_{sig} = the percentage number of simulations that resulted in a significant difference, where F>E indicates a greater score for filled intervals, and E>F indicates a greater score for empty than filled intervals, d_m = mean Cohen’s d value, where a positive d indicates a greater score for empty than filled intervals, d_{sd} = standard deviation of Cohen’s d values.

Figure 4. Histograms displaying the resulting t-statistics (top row), p-values (middle row), and Cohen's d values (bottom row) for comparisons of total number of guesses (left column), total number of correct answers (centre column), and resulting temporal difference threshold (right column) following a 74% increase in pacemaker rate, simulating the performance for filled durations as compared to empty durations.

Modelling Results for a 10% Increase in Pacemaker Rate (Click Trains)

Around 55% of simulations found a significant improvement in temporal sensitivity (lower thresholds) for the simulated filled interval condition as compared to the empty condition. We will now repeat the modelling procedure to investigate the percentage number of simulations that will find significant differences between temporal difference thresholds following simulated click trains versus silence. **Figure 5** displays the relevant histograms for these comparisons, and **Table 4** contains the associated t -statistics and Cohen's d values, in addition to the percentage of simulations that resulted in a significant difference for the three comparisons.

Table 4. Modelling results for a 10% increase in pacemaker rate across 10,000 simulations.

Comparison	t_m	t_{sd}	% _{sig}	% _{sig} C>S	% _{sig} S>C	d_m	d_{sd}
Total Guesses	0.99	1.15	19.91	0.47	19.44	0.05	0.06
Total Correct	-0.28	1.15	9.09	6.70	2.39	-0.03	0.11
Threshold	0.42	1.16	10.62	1.96	8.66	0.03	0.08

Note. t_m = mean t -statistic, where a positive t indicates a greater score for silence than click trains, t_{sd} = standard deviation of t -statistics, %_{sig} = the percentage number of simulations that resulted in a significant difference, where C>S indicates a greater score for click trains, and S>C indicates a greater score for silence than click trains, d_m = mean Cohen's d value, where a positive d indicates a greater score for silence than click trains, d_{sd} = standard deviation of Cohen's d values.

Figure 5. Histograms displaying the resulting t-statistics (top row), p-values (middle row), and Cohen's d values (bottom row) for comparisons of total number of guesses (left column), total number of correct answers (centre column), and resulting temporal difference threshold (right column) following a 10% increase in pacemaker rate, simulating the performance following click trains as compared to silence.

Discussion

The 74% increase in pacemaker rate (simulating the effect of filled versus empty durations) led to significantly fewer ‘guesses’ in almost 100% of simulations, though constituting a small effect size on average ($d = 0.27$). This shows that greatly increasing the number of pulses accumulated during both durations made it easier for the simulated participants to tell them apart, due to the concurrent greater difference between them. This in turn led to a higher number of correct answers in filled versus empty simulations 31% of the time. As the task converges at 75% accuracy, thus constraining the number of correct answers to a degree, this measure constitutes a coarse measure of improvement but is nonetheless interesting that it increased. Finally, these benefits for filled compared to empty intervals translated into significantly lower temporal difference thresholds in 55% of cases (also with a small effect size, $d = 0.15$). Therefore, while there were significantly fewer guesses following the higher pacemaker rate in almost all simulations, the actual amount of these averted guesses only improved subsequent temporal sensitivity around half the time. This may be due to the positions in the staircase where these guesses were averted.

Meanwhile, the 10% increase in pacemaker rate (simulating the effect of click trains versus silence) led to a significantly lower number of guesses in 19% of simulations. This suggests that a fifth of the time, click trains aided in increasing the proportion in Equation 1 above and beyond the decision threshold, compared to silence (though with a much smaller effect size of $d = 0.05$). However, this benefit of click trains led to significantly more correct answers only 7% of the time. This in turn led to significantly lower thresholds for the click train simulations than the silence simulations in 9% of cases. Here, the distribution of Cohen’s d values centred on 0.03.

Taken together, it appears as though a mixture of Possibility 2 and 3 is correct. That is, scalar timing theory does predict higher temporal sensitivity with a faster pacemaker. However, a 10% increase is too small to be reliably detected, so click trains will not reliably improve temporal sensitivity.

General Discussion

Our empirical investigation found no significant differences between temporal difference thresholds following click trains, white noise, and silence. In addition, Bayes factors favoured the data given the null hypothesis with strong to moderate evidence. We identified three possibilities following these empirical findings, which could be dissociated by the results of 10,000 simulations of a 10% and 74% increase in pacemaker rate.

Once the best fitting combinations of pacemaker rate and drifting rate were identified for each participant, we simulated threshold performance for filled versus empty intervals, and threshold performance following click trains versus silence. While filled intervals were found to lead to significantly higher sensitivity than empty intervals in 55% of simulations, click trains led to significantly higher temporal sensitivity than silence in only 9% of the simulations. Both of these sets of simulations returned small effect sizes on average. This suggests that scalar timing theory does predict improved temporal sensitivity for higher pacemaker rates, but the relatively small increase in pacemaker rate occasioned by click trains is not enough to lead to significantly higher temporal sensitivity the majority of the time.

If one were to be conservative, arguing that finding significance in 9% of cases is not sufficiently greater than 5% (chance levels), the reader would subscribe to Possibility 2. This suggests that scalar timing theory does predict improved temporal sensitivity with

a faster pacemaker (e.g. filled versus empty, auditory versus visual) but the 10% increase occasioned by click trains is undetectable due to small effect and relatively large proportion of noise. However, if one were to be less stringent, treating the simulation results similar to a significance test (where 5% is a hard boundary), the reader would subscribe to Possibility 3. This suggests that the experimental results encountered a Type II error, and an empirical replication would be more likely to find that click trains lead to significant improvements in temporal sensitivity.

We are inclined to subscribe to Possibility 2, but regardless of one's alignment to these two possibilities, we have found that the effect of click trains on the temporal difference threshold task appears to be too small to be reliably detected, despite the marked effect of click trains on other timing tasks, and of other temporal illusions on the temporal difference threshold task.

Future work may wish to replicate our experimental investigation, to ascertain the likelihood of Possibility 3. If a replication similarly found no significant effect of click trains on temporal difference thresholds, with Bayes factors as high or higher as those reported here, this would provide more evidence against Possibility 3 and for Possibility 2. Future research in this area could also investigate the effect of visual flickers on thresholds, as previous work has found similar effects to click trains on a range of tasks (Droit-Volet & Wearden, 2002; Herbst et al., 2015; Herbst et al., 2013; Ortega & Lopez, 2008; Treisman & Brogan, 1992; Wearden et al., 2017). Finally, the interested reader may wish to explore our scalar timing model of temporal difference thresholds using a different parameterisation, though we argue that our modelling decisions are sensible and well-reasoned. We have, at the very least, been diligent in trying to characterise the mathematical predictions and embodiment of scalar timing theory as accurately as possible.

In summary, click trains increase subsequent judgements of duration by approximately 10%, an effect found in many timing tasks, including verbal estimation, temporal generalisation, and temporal bisection. The effect of click trains had not yet been examined on temporal sensitivity, though some had argued that a faster pacemaker would entail higher sensitivity. Our experimental investigation found no significant improvement in temporal sensitivity; Bayes factors favoured the data given the null hypothesis with strong to moderate evidence. This suggested three possibilities, which we investigated by simulating a 10% increase in pacemaker rate in a scalar timing model of thresholds. We found this simulation to lead to a significant improvement in temporal sensitivity in only 9% of 10,000 simulations. Therefore, scalar timing theory does predict improved temporal sensitivity for a faster pacemaker, but the effect of click trains appears to be too small to be reliably found in a temporal difference threshold task.

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Open Practices Statement

The data and materials for the behavioural and computational investigations are available at <https://osf.io/348fm>. Neither investigation was pre-registered.

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