Experimental and Computational Analyses of Strategy Usage in the Time-Left Task

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Abstract

This paper investigates the usage of strategies in the Time-Left task (Gibbon & Church, 1981). In that task, participants are assumed to compare temporal intervals on their subjective timescales (i.e., do temporal arithmetic), yielding different hypotheses for linear and nonlinear subjective time. Here we present an experiment and ACT-R model simulations that show that participants probably use strategies different from temporal arithmetic. Usage of other, alternative strategies would allow for any subjective timescale. As the interpretation of Time-Left results critically depends on temporal arithmetic, these results invalidate the Time-Left task for distinguishing between different internal timescales.

Keywords: Time-Left Task, time perception, linear vs nonlinear time, computational models.

Introduction

Time plays an intricate part in many of the things we do in our professional and everyday lives. For example, at the beginning of a day at the office, we know beforehand that we can compose and send a short e-mail in the time that it takes for the coffee machine to finish percolating; the loading time of a web page exceeding some time interval predicts reasonably well failure to load at all; and, a long enough moment of silence in a conversation is a cue to the listener to respond to what has just been said.

Considering the ubiquitousness of time dependencies in many of the things we do, it is striking that only so little is known about how time is perceived or represented internally. One theory of temporal processing is the Scalar Expectancy Theory (SET, Gibbon, 1977) that postulates that time is represented in a linear fashion. Although Staddon and Higa (1999) have extensively argued that SET contains a number of questionable assumptions, it still is the most influential theory on time perception.

Other theories have assumed different types of internal representations. For example, Staddon and Higa (1999) have proposed a logarithmic representation and we, in earlier work (Van Rijn & Taatgen, 2008; Taatgen, Van Rijn, & Anderson, 2007), have proposed a representation that is based on increasing intervals.

That the issue of the type of internal representation is still not resolved is striking given a publication by Gibbon and Church in 1981. In that paper, Gibbon, author of SET, and Church, associated with a paper proposing a logarithmic representation (Church & Deluty, 1977), joined forces to conceive an experiment that would identify the underlying timescale. This experiment is the Time-Left task and it is claimed that the results refute the logarithmic representation.

However, we will argue that the different types of strategies that might be used to perform this task make it impossible to derive any firm conclusions from Time-Left data.

Time-Left Task

In the original Time-Left experiment (Gibbon & Church, 1981), rats were initially trained to estimate two individual temporal intervals. The rats were placed in a chamber in which two levers could appear. In some trials, a lever was inserted at the left that, if pressed, would provide the rat with a food reward after 60 seconds. In the other trials, a lever was inserted at the right, which primed food after 30 seconds. After being trained on these intervals, the rats were presented combined trials, in which the entry of the left lever indicated the start of a trial. Then, after 15, 30 or 45 seconds in the trial, the right lever was inserted. When reinforcement on either lever was received, both levers were removed, the trial ended and an inter-trial interval was presented.

If rats experience time linearly, they should favor the short interval (right lever) at 15 seconds, because the time left before food is presented is (60 - 15 =) 45 seconds for the left lever, and 30 seconds for the right lever. At 45 seconds they should favor the long interval because the remaining time is smaller than the short interval (60 – 45 < 30). At 30 seconds they should be indifferent and favor both intervals equally likely. The entry point at which both levers are selected equally likely is referred to as the indifference point.

On the other hand, if rats experience time on a logarithmic scale, a different behavioral pattern should emerge. Assuming a logarithmic interval, subjective time increases progressively slower than real time. Consequently, at 30 seconds, rats should already favor the long interval over the short interval as the remaining subjective time (log(60) - log(30)) is smaller than the subjective duration of the short interval (log(30)).

The results of Gibbon and Church's (1981) experiments did not show any evidence of nonlinearity: The point where rats and pigeons were indifferent was close to the linear optimum. Also, the indifference point increased as the absolute duration of the long and short intervals increased, which is to be expected on the basis of a linear timescale (with predicted indifference points of 30 - 15 = 15 versus 60 - 30 = 30), whereas it would remain constant if time is experienced logarithmically (log(30) – log(15) = log(60) – log(30)).

These results led Gibbon and Church to conclude: "In summary, the data from both experiments argue that mean subjective time is approximately linear in real time", but immediately mediate this conclusion by stating: "The alternative logarithmic process is ruled out *if subjects perform these tasks by comparing the two delays to food on their subjective time scale*." (p.106, our emphasis).

Although the main resonance of this work seems to proof that time is perceived linearly, some researchers have challenged this notion and proposed alternative explanations in line with Gibbon and Church's caveat (e.g., Cerutti & Staddon, 2004; Dehaene, 2001; Gallistel, 1999; Staddon & Higa, 1999). For example, Dehaene (2001) has shown in a numerical analogue of the time-left task that behavior can be modeled as a strategy in which the best response alternative is learned to be associated with the time elapsed since the start of a trial. As the underlying timescale is not used in determining an answer using this *associative* strategy, any relation between subjective and real time would yield similar behavior. Dehaene also indirectly raised the issue that the original Time-Left explanation assumes relatively advanced arithmetic skills. As these skills are not commonly attributed to non-humanoids, it might be that other strategies have indeed contributed to the observed results.

Human Analogue of Time-Left Task

Wearden (2002) tested whether humans show similar behavior in the Time-Left task. In his human analogue of this task, the two durations were presented as two trains that one could take to a destination. The longer interval is represented by a slow train. Sometimes, during travel with the slow train, a special train becomes available to which participants can transfer. This train is special in that it always takes the same amount of time to reach its destination, regardless of the time already travelled with the slow train. This setup has an underlying one-to-one mapping to the original setup. The results of the experiments reported by Wearden (2002) support the original conclusion that the internal representation is linear.

Although not discussed by Wearden, it is still the case that these widely cited conclusions only hold when participants do indeed *"perform these tasks by comparing the two* [intervals] *on their subjective time scale".* Thus, to be able to fully appreciate the data presented by Wearden, it has to be ruled out that participants have done anything but comparing the two intervals: Using alternative strategies might remove the necessity of performing temporal arithmetic and therefore render the results of Time-Left experiments inappropriate for the discrimination of linear and nonlinear subjective time.

Three Strategies for Accurate Performance

A review of the literature suggested two strategies that match the earlier reported Time-Left behavior. The first strategy is the original Gibbon and Church (1981) *temporal arithmetic* account. According to this strategy, participants wait until the start of the second interval is signaled, calculate *time left* in the long interval (i.e, use temporal arithmetic), and then compare that value with the short interval to decide which interval leads to fastest reward (i.e., shortest travel time).

The second strategy is the earlier discussed *associative account* proposed[1] by Dehaene (2001). According to this strategy, participants learn during the experiment to associate with each entry point the best response option (leading to shortest travel time).

A third possible strategy is based on informal feedback of (human) participants in pilot Time-Left studies ran in our lab. In the debriefing sessions, a frequently reported strategy was using a *switch point*: Participants reported that they waited for an estimated point in time after which enough time has passed to warrant not switching to the short interval. In many of these reports that were in fact based on experiments in which the short to long ratio is 1:2, participants mentioned using the short interval as switch point.

It is important to note that the Time-Left task can only be used to distinguish between linear and nonlinear internal timescales if participants use the first, temporal arithmetic strategy. The other two strategies are agnostic with respect to the internal representation.

To assess the prevalence of these strategies, we devised a new human analogue of the Time-Left task. As pilot studies indicated that the train-travel cover stories confused rather than helped participants in understanding the task, we presented the experiment without a semantic cover story. The main differences with earlier human Time-Left experiments are that we also measured the RTs associated with each response and that we removed a secondary task to name rapidly presented digits. The digit-naming task was introduced by Wearden to prevent participants from using explicit timing strategies such as counting, but our pilot studies indicated that the performance penalty associated with this task was too high to warrant inclusion. Instead, we instructed participants not to use any explicit timing strategies. With respect to the RT measurements, it should be noted that it is often difficult to analyze RTs in a relatively off-line task. However, earlier work has shown that RTs can yield informative insights in which strategies are used (c.f., Van der Maas & Jansen, 2003, who assessed the validity of the strategies proposed by Van Rijn, Van Someren, & Van der Maas, 2003).

For each of the three strategies, specific predictions can be made with respect to the RT patterns and the change of behavior during the experiment. With RT patterns, we refer to the pattern of RTs when the RTs are plotted against the onset of the short interval (see Figure 4 for an example). With respect to the temporal arithmetic strategy, especially

[1] Although Dehaene's association hypothesis was associated with a numerical analogue of the Time-Left task, he argues that this hypothesis also holds for the temporal Time-Left task (S. Dehaene, personal communication, October 2008).

if considered in the context of SET, the expected RT profile depends on the time it takes to calculate time left in the long interval and compare that value with the short interval. If all arithmetic problems take equally long at each entry point (of the short interval), the temporal arithmetic strategy predicts a flat profile. If we allow for variable durations to solve the problems, a declining slope would be expected, as solving, for example, 30 - 29 takes less time than solving 30 - 1 (Sprenger & Van Rijn, 2005). Moreover, as the decision to respond *short* or *time-left* (in long interval) is based on a single process, no qualitative difference is expected in the response patterns for both options. With respect to changes in behavior, no specific effect is expected if one assumes that at the start of the experiment both short and long durations are accurately represented.

The associative strategy predicts that RT profiles are flat, because all entry points are equally likely and therefore equally trained. However, the associative strategy does predict a clear change in behavior over the experiment. As the associations need to be learned over time, this account predicts that the performance of the participants improves with more training.

The *switch point* strategy predicts more pronounced RT profiles. It predicts an increasing slope for the RTs associated with the *short* responses, but a decreasing slope for the *time-left* responses. This effect can also be described as a negative effect of being closer to the switch point. When a trial starts, a participant that aims to respond as fast as possible could prepare the *short* response as at the start of the trial *short* clearly is the best option. Thus, all motor preparation for a *short* response can be made. However, the closer the time-in-trial gets to the switch point, the less likely it is that *short* is the appropriate response, so, more time is needed to decide what is the best response. When the time-in-trial passes the switch point, the same process applies in reverse.

Experiment 1

Apart from the analyses suggested above, which could be run on a Time-Left dataset without any experimental manipulation, we also included a manipulation that could provide additional insights in the viability of the different strategies: If participants really use the short interval as an indication of the switch point, short and long intervals with a ratio slightly less than a half (e.g., 3.75s/8s or 2.75s/6s instead of 4s/8s or 3s/6s), so-called *competitive* ratios, yield opposite shifts in indifference point for the switch point strategy and temporal arithmetic. The switch point strategy predicts that, if participants use the short interval as switch point, the indifference point will be at 3.75s, whereas the temporal arithmetic account predicts the indifference point to be at 8 - 3.75 = 4.25s. Thus, changing the duration of the short interval from 4 to 3.75 seconds would cause a shift of the indifference point to the left for the switch point strategy whereas it would cause a shift to the right for temporal arithmetic.

Method

Participants Twenty-five Psychology and Artificial Intelligence students participated in exchange for course credit. Five students were excluded from the analysis because of not adhering to the instructions.

Design, Stimuli and Procedure The experiment consisted of two blocks. In the half-ratio block, participants received a short and long interval with a ratio of a half (4 and 8 seconds or 3 and 6 seconds). In the competitive-ratio block, participants received a short and long interval with a ratio of less than a half (3.75 and 8 seconds or 2.75 and 6 seconds). Each participant received one 8s and one 6s block, the order of half- and competitive-ratio blocks was counterbalanced.

During the first 16 (of 32) practice trials, participants were presented both short and long intervals 8 times. All trials started with a fixation cross, for 1000ms. Next, either the short or the long interval was presented. For the short interval, a blue circle was displayed at the right of the fixation point, for the long interval a green circle was displayed at the left. After the interval ended (i.e., after 2.75, 3, 3.75, 4, 6 or 8s), the circle was removed from the screen. The screen remained blank for 500ms, after which the same circle was presented again. However, instead of automatically disappearing, the participants were asked to press the spacebar when they thought that the circle was displayed for the same duration as in the previous presentation. After the response was given, the circle disappeared, and feedback was presented. If the estimated duration was more than 20% off, feedback stated that the response was *much too early/late*, if it was more than 10% off, feedback stated that the response was *too early/late*. If the feedback deviated less than 10%, the feedback stated that the response was *correct*. Feedback was displayed for 2500ms. After these 16 practice trials, participants received another 16 practice trials that were similar except for the removal of the presentation of the interval, requiring the participants to estimate the durations from memory.

After the practice trials, participants were instructed that in the next block, both circles would appear at different onsets. Their task was to judge which circle would disappear first, and to select that circle by pressing the "V" key if they thought that the left, green circle (long interval) would disappear first, and the "N" key if they thought that the right, blue circle (short interval) would disappear first. The "V" response is referred to as the *time-left* choice, as participants preferred to stay with that option and wait for the time that is still left in the long interval. As soon as a choice was made, the other circle was removed from the screen as not to give any feedback about the correctness of the response, and the selected circle remained on the screen for the remainder of the associated interval its duration. All experimental trials started with the presentation of a fixation cross for 1000ms. Next, the green circle was presented, indicating the start of the long interval. Then, after a fraction of the long interval had elapsed (n/10, where n is selected from [1,..,9], resulting in n entry points), the blue circle was presented, indicating the start of the short interval. Participants were provided a response window of 1500ms. No explicit feedback was given, except for when the response was too slow.

t(16.51) < 1). Apart from the very similar indifference points observed in all conditions, it is also noteworthy to mention that the 95% confidence intervals are more than three times the experimental manipulation (of 250ms): -463

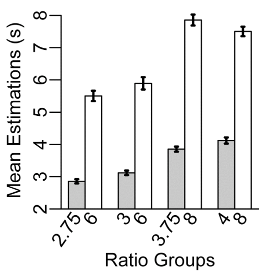

Figure 1: Interval estimations (and SEs) per ratio group in the last 16 trials of the practice block.

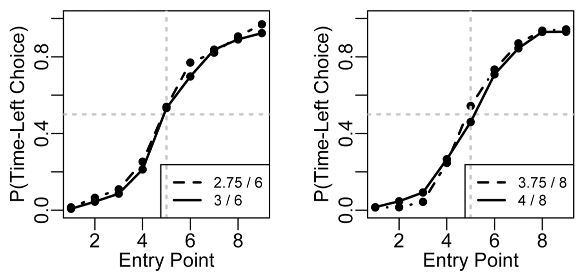

Figure 2: Proportion Time-Left choice at entry points 1 to 9, for the 2.75/6, 3/6 groups (left), 3.75/8 and 4/8 groups (right).

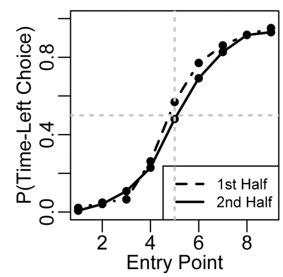

Figure 3: Proportion Time-Left choice in 1st and 2nd half of the experiment block, for all groups combined.

Results

Practice Trials For both the *switch point* strategy and *temporal arithmetic*, Time-Left behavior (in the experimental trials) depends on how well the intervals are learned during the practice trials. Visual inspection, see Figure 1, shows that all intervals have been learned relatively well. Furthermore, to be able to make valid comparisons between the half-ratio and competitive-ratio groups, estimations of the long intervals should not differ, as these are equally long in the half-ratio and competitive ratio groups. However, estimations of the short intervals should differ, as these are not equally long in the half-ratio and competitive ratio groups.

The data support these requirements. The mean estimations of the long interval do not significantly differ for the 3.75/**8** and 4/**8** groups: t(20.83) = 1.57, p = .131. The same applies to the 2.75/**6** and 3/**6** groups: t(20.71) = -1.57, p = .133. The mean estimations of the short intervals do significantly differ for the **3.75**/8 and **4**/8 ratio groups: t(19.94) = -2.16, p = .043. The same applies to the **2.75**/6 and the **3**/6 groups: t(20.92) = -2.74, p = .012. Consequently, the presence/absence of an effect of ratio on indifference point is not to be attributed to inaccurate, differential representations of the intervals.

Indifference points Proportion of time-left choice was calculated for each entry point, per participant and condition. Remember, entry point is a fraction (1/10, ... 9/10) of the long interval. Figure 2 presents the overall proportion time-left choice for half- and competitive-ratio conditions. Cubic trends (or S-curves) were fitted on the time-left proportions per participant. The location at which the cubic trend crossed P(Time-Left)=.5 was taken as that participant's indifference point.

Contrary to our predictions, the indifference points do not significantly differ for the half- and competitive-ratio conditions. (4/8 vs. 3.75/8: t(16.86) < 1, 3/6 vs. 2.75/6

up to 524ms for the difference between the 4/8 and 3.75/8 groups and -329 up to 544ms for the difference between the 3/6 and 2.75/6 groups. As the 8 and 6-based groups do also not differ (in choice and RT behavior), we have collapsed the data over these manipulations in the remainder of this paper.

Learning effects Time-left preference functions in the first and second halves of the experimental blocks are compared to investigate the presence of the *associative strategy* (see Figure 3). Recall that an increase in the slope of the time-left preference function over the two halves would be the signature of associative learning. Visual inspection of Figure 3 shows that the time-left preference function is not steeper in the second half of the experiment. Within-subjects comparisons of slopes also do not hint at a more pronounced time-left preference function (average difference between slopes for the 1st half - 2nd half: .01, t(45) < 1). However, the indifference points do shift (with -.3 entry point) when the first and second half of the experiment are compared (t(45) = -2.69, p = .01).

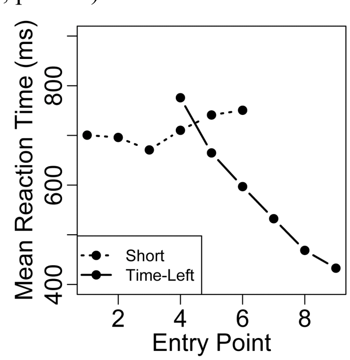

Figure 4: Mean reaction time (in ms) for responses on the short and long intervals, at entry points 1 to 9.

Reaction time Figure 4 presents mean RT curves per entry point, plotted separately for short and time-left responses.

As the number of long responses for entry points 1 to 3, and the number of short responses for entry points 7 to 9 was limited, we did not include these data points in Figure 4.

For both response alternatives, mean RT is (linearly) regressed on entry point. Analyses confirm the pattern visible in Figure 4: For short responses, the RT increases with entry point, as indicated by the significant positive slope: (β = 12.15ms, $t(22) = 2.45$, $p = .023$). On the other hand, mean RT for time-left responses decreases with entry point as the slope is estimated at -68.71ms ($t(22) = -8.97$, $p < .001$).

Discussion

This experiment was conducted to assess which of the three identified strategies was predominantly used in the Time-Left task. The picture that emerges from the data does not univocally support one strategy. The most informative data comes from the RT data. As differential effects are found for the *short* and the *time-left* responses, the conclusion seems warranted that the underlying strategy cannot be a continuous function of entry point. This rules out the usage of the associative strategy, as this account predicts a flat RT profile. It is also unlikely that a SET-based temporal arithmetic explanation can account for the found results, as in its current form SET does not identify different processes for both response options. The account that comes closest to the data is that based on debriefing interviews in our pilot studies: the switch point strategy. However, although the slopes of both RT profiles fit qualitatively well, our initial assessment predicted similar slopes in absolute terms for the *short* and the *time-left* responses. The difference between our prediction and the data could be explained by assuming that participants do not completely prepare the *short* response before the switch-point, as they are not yet sure whether that will be the correct response. Instead, they only start preparing the *time-left* response when the switch-point has passed. Additionally, the data corroborates the assumption that additional time is needed to decide between both options if current time is close to the switch point. Given these additional assumptions, the switch point strategy fits the RT data best.

If we look at the learning pattern, the strongest prediction was made by the associative strategy, as participants who follow this strategy need experience to perform accurately. However, no such learning effects were observed. The accuracy became slightly better, but no difference in slope was observed. As both temporal arithmetic and the switch-point strategies could also explain a shift to higher accuracy (as more precise representations are learned), the conclusion from the analysis of learning patterns should be that the associative strategy does not play an important role in human Time-Left behavior.

Interesting results were found when the half-ratio and competitive-ratio conditions were compared. Our assumption was that using a short interval slightly shorter than .5 times the long interval yields either of two behaviors. If participants would use the short interval as switch point, the indifference point would be similar to the short interval (i.e., 2.75s or 3.75s instead of 3s or 4s). However, if participants use the temporal arithmetic strategy proposed by Gibbon and Church (1981) and Wearden (2002), or the associative strategy, the indifference point should be close to 6 - 2.75 = 3.25s or 8 - 3.75 = 4.25s. However, neither effect was found. The indifference points in the half-ratio conditions did not differ from those in the competitive-ratio conditions, disproving the predictions of all three strategies.

To sum up: the *associative* strategy is supported by none of the analyses; the predictions derived from the *temporal arithmetic* strategy do not fit the RT data nor the half/competitive ratio analyses; and the *switch point* strategy, although it can explain the found RT data, predicted a different result for the half/competitive ratio analyses.

Time-Left Model

Given that the switch point strategy fared best, the question is whether this strategy can be reconciled with a lack of an effect in the half/competitive ratio conditions. Hereto, we implemented the 3.75/8 and 4/8 ratios of the Time-Left experiment as a model in the cognitive architecture ACT-R (Anderson, 2007). This model is a complete model of the task in that it produces both choice and RT behavior.

The model uses a pacemaker-accumulator that yields a nonlinear scale because of increasing inter-pulse lengths (Van Rijn & Taatgen, 2008; Taatgen, Van Rijn, & Anderson, 2007) and uses the standard ACT-R declarative memory system in which the durations of the short and long intervals are stored. This system complies with the Weber-Fechner law due to pulse-by-pulse variability that is a function of the pulse length. The model is based on the following assumptions:

(1) A switch point strategy is used, with the short interval as switch point (i.e., 3.75 or 4);

(2) Around the switch point, temporal uncertainty (because of the similarity between switch point and current time) causes a delay in the execution of a response;

(3) After the switch point has passed, a top-down mechanism selects the *time-left* response in advance of the actual response execution;

(4) All parameter settings of the temporal system are copied verbatim from Van Rijn and Taatgen (2008).

After the practice trials, the model's internal representations result in similar behavior as shown in Figure 1: A significant difference between the estimations of the short intervals (of 3.75 and 4 seconds), but no significant difference between estimations of the long intervals. Variability is greater at the long intervals (than at the short intervals), which is in correspondence with the Weber-Fechner Law.

The RT patterns of the model, presented in the right panel of Figure 5, show a clear dissociation between *short* and *time-left* RTs. This pattern is caused by assumptions (2) and (3) reported above. With respect to the *time-left* RTs, a participant can anticipate a *time-left* response as soon as the current time becomes larger than the switch point, causing the associated RT to decrease because of preparatory processes. Top-down response selection does not occur at the start of a trial because of startup costs and the (increasing) likelihood of having to switch response option. The *short* RTs (slowly) increase because the closer the entry point gets to the switch point, the more likely it is that the model confirms its decision by a second readout of the accumulator (that counts ticks in time). This additional process slightly increases reaction times. Note that even if some participants did prepare a response in the early phases of a trial, the mean reaction time would still be greater for the first entry points than for the last entry points.

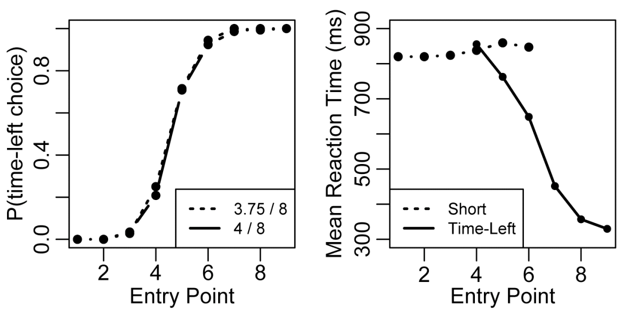

Figure 5: Model results. Left panel depicts the Time-Left Preference for both half/competitive conditions; RT behavior is depicted on the right.

Apparently, the model can account for the (human) RT data, however, the main question was whether it could also account for the half/competitive ratio results. As can be seen in Figure 5 (left panel), the model replicates the lack of an effect in the half/competitive ratio conditions, which is partly caused by pacemaker-variability. That variability causes multiple pulse-counts (stored in declarative memory) to be associated with the short interval. Consequently, retrieving the pulse-count associated with the short interval does not always yield the same amount. Because of pacemaker-variability and multiple pulse-counts, the indifference points in the 3.75/8 and 4/8 groups do not significantly differ, mimicking the results found in the human data.

General Conclusions

In 2007, Wearden and Jones have argued that although a number of procedural and theoretical considerations make it difficult to interpret Time-Left data gathered using animals these constraints "apply with less force to the human time-left analogue" (p. 1292). Nevertheless, they argue that other tasks might be more appropriate to distinguish between linear and nonlinear time.

This study shows that it is not just more appropriate to use other tasks to distinguish between linear and nonlinear timescales, it is *necessary.* That is, the current experiment and simulations show that participants use strategies different from the temporal arithmetic strategy proposed by Gibbon and Church (1981) and Wearden (2002). As the interpretation of Time-Left results critically depends on the usage of temporal arithmetic, the absence of that strategy invalidates the Time-Left task for distinguishing between different internal timescales.

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