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Full Length Article

# Unfolding event structure distorts subjective time

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ABSTRACT

Our experience of time is often distorted in striking ways. Although prior work has shown that boundaries between events can shape temporal perception and memory, less is known about whether, or how, the structure *within* an event can affect our experience of time as it unfolds. In this study, we asked whether an event's internal structure (i.e., its beginning, middle, and end) systematically biases representations of duration. Across four experiments, participants listened to sequences of tones and either reproduced or judged their durations. We consistently found robust and systematic biases in subjective time: Beginnings were compressed, endings were expanded, and subjective time lengthened progressively over the course of the sequence. These results reveal a distortion in temporal experience that arises not from the transitions between events, but from the way we parse and organize time within them.

## 1. Introduction

The human mind is not well-equipped to veridically represent *when* events occurred or *how long* they lasted. Rather, we rely on external 'tools', whether clocks, calendars, or records to accurately represent the passage of time (Cooperrider, 2025). However, these tools are fallible and not always at our disposal, so we instead rely on the mind's internal mechanisms to estimate time. For example, imagine you were asked to recall which was longer — your first meeting of the day, or your last one. This judgment might be informed by many cues other than the passage of time itself (e.g., who the meeting was with, how excited you were about it, whether there was something else on your mind, or even simply the fact that it occurred at the beginning or the end of your work day). Or imagine you were asked to recall the first time you met a friend; you probably would not pull out your calendar and point to an exact date. Instead, you would rely on context clues (you were at a local park, in the Spring, while you were in college) or other noisy mental heuristics.

Indeed, our internal representations of time are not just noisy, but subject to *bias* from a broad range of factors. For example, our sense of time can be stretched or compressed by high-level factors such as emotion (e.g., Droit-Volet & Meck, 2007) and surprisal (e.g., Ulrich et al., 2006), as well as low-level factors like eye blinks (Grossman et al., 2019), attention (Tse et al., 2004), and stimulus repetition (e.g., Sherman & Yousif, 2025). Yet another factor which can powerfully distort subjective time, in both perception and in memory, is *event structure* – that is, how we segment our experiences into discrete events (e.g., transitioning from and demarcating your first vs. second meeting of the day).

Event representations alter the way that time is subjectively experienced in the moment. Experiences which contain an event boundary are reliably judged as shorter than equivalent intervals without a boundary (Bangert et al., 2020; Liverence & Scholl, 2012; Sherman et al., 2023; Yousif & Scholl, 2019), perhaps because event boundaries trigger a 'flushing' of working memory for information that occurred prior to the boundary. Event boundaries not only influence judgments of *cumulative* time, but also distort the perception of time for information encountered proximal to the boundary (Ongchoco et al., 2023), again suggesting that our temporal experience is fundamentally shaped by event structure.

The influences of event structure on representations of time are not only present in shorter term perception and working memory, but also reflected in the way that temporal information is encoded into long-term memory. For example, contrary to the compression observed at shorter timescales, event boundaries lead to a subjective expansion of time in memory, such that items spanning a boundary are remembered as having occurred farther apart in time than items which did not span a boundary (Clewett et al., 2020; DuBrow et al., 2024; Ezzyat & Davachi, 2014; Faber & Gennari, 2017). This cross-boundary expansion of time

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may be a consequence of the way event boundaries serve to efficiently organize our memories — by cognitively and neurally separating out memories based on shared content and context (Clewett et al., 2019).

The vast majority of work on event representation and time has focused on the influence of event *boundaries* on time — that is, how the presence of a boundary alters our perception of and memory for time (see Yates et al., 2023). However, events are more than the boundaries between them. Events contain substantive content (e.g., the agenda of a meeting). Although some work has addressed how people represent the content, or *internal structure*, of an event (e.g., Hafri et al., 2018; Ji & Papafragou, 2020; Ji & Papafragou, 2022; Moens & Steedman, 1988), little is understood about whether that internal structure also influences our temporal experience.

Effects of primacy and recency on memory (well-known effects that memory is enhanced for the beginning and ending of a sequence; Kahana et al., 2024) could be construed as one way in which an event's internal structure affects its memory. Although primacy and recency effects are not traditionally characterized as being about events, there is evidence linking primacy/recency effects to event structure. For example, there is a 'local primacy effect' within events, such that items at the start of an event are better remembered (Pu et al., 2022). Further, recent work suggests that these primacy and recency effects may not simply reflect enhanced recognition or recall. Beginnings and endings of events can also be uniquely expanded in temporal memory, such that they become over-represented on people's mental timelines (Yousif et al., 2024). This latter effect manifested in long-term memory, and it is unclear whether similar biases would manifest for more immediate judgments of temporal experience.

In the current study, we sought to understand how the internal structure of an event — e.g., its beginning, middle, and end — influences the subjective experience of time. Across four experiments, we presented participants with sequences of tones and had them reproduce or judge the durations of the tones. We observed robust and systematic distortions in time based on the sequential structure. Beginnings were temporally contracted, endings were temporally expanded, and there was a continuous expansion of subjective time throughout the event (i.e., as an event proceeded, participants judged each unfurling component of the event as increasingly longer). Together, these data suggest that the temporal structure within a single event can strikingly influence how time is experienced.

## 2. Experiment 1

In a first experiment, we examined whether people's subjective sense of time systematically varied within an event. We presented participants with a sequence of auditory tones, with one tone varying in length (or all tones equal), and subsequently asked them to reproduce the entire sequence. We then assessed whether a tone's position in the sequence biased participants' duration reproductions.

### *2.1. Methods*

#### *2.1.1. Preregistration and data availability*

All aspects of the procedure and design (for all experiments) were pre-registered prior to data collection. Those preregistrations, as well as the data for all experiments, can be found on our OSF page (https://osf.io/9seuz/).

#### *2.1.2. Participants*

Participants in all experiments were recruited via the Prolific platform. All participants (in all experiments) were adults 18 years or older residing in the United States who were proficient speakers of English. Per our preregistered criteria, the final sample size was 50 participants, after exclusions and replacements. Participants were excluded if (a) they failed to complete the task (e.g., they did not complete all the trials), (b) their responses revealed overt negligence or inattention (e.g., they reproduced extremely short durations on nearly all trials) or (c) they revealed some significant misunderstanding of the task. We also excluded individual trials if the total reproduced duration (summed across the five tones) was greater than 3 SDs from the mean across all participants and all trials. These criteria were the same for Experiments 1 through 3. In Experiment 1, 8 participants were excluded (and replaced) for failing at least one of these criteria, and 6 individual trials were excluded.

All participants provided informed consent, and the study was approved by the relevant Institutional Review Board.

#### *2.1.3. Task design and procedure*

All experiments were administered online via a web-based interface using custom JavaScript code.

Each trial consisted of a listening phase followed by a reproduction phase. Participants were informed that they would be hearing a sequence of tones and then would have to reproduce the same sequence. Trials were separated by a 1750 ms blank inter-trial interval.

During the listening phase, a sequence of five tones was played while showing a blank screen with instructions to listen carefully to the tones (Fig. 1A). The tone sequences had a total duration of either 4 s or 8 s, and each tone played in one of three pitches ("A4", "A5", or "E5") randomly assigned to the different temporal positions (with the constraint that no two tones of the same pitch could play successively). There was a 350 ms pause between each tone. On a third of the trials, all tones were of equal length. On the other two-thirds of trials, one tone varied by ±25 % or ±50 %, while the other four tones were of equal length. For example, in a 4-s trial with the middle tone varying by +25 %, the following sequence would play: a 761.9 ms tone, a 350 ms pause, a 761.9 ms tone, a 350 ms pause, a 952.4 ms tone, a 350 ms pause, a 761.9 ms tone, a 350 ms pause, then a 761.9 ms tone. We included twice as many equal trials as, e.g., +25 % trials, to account for the fact that equal (0 %) trials are not bidirectional. All variables (sequence duration, which of the five tones was deviant, and degree of duration deviance) were fully counterbalanced across 60 trials.

Immediately after the listening phase, participants underwent the reproduction phase, during which they were prompted with the instruction: "Please replicate the timing of the sequence you just heard. Hold the spacebar down to play the tones." (Fig. 1B). Specifically, participants would respond by holding down the spacebar five times in succession — similar to how one would press a key on a piano — to match the perceived duration of each tone in the sequence (in order). Participants' press durations were used as a proxy for perceived tone duration. The pitches during the reproduction phase matched the order of pitches presented in the listening phase. We did not enforce any response deadlines during the reproduction phase.

### *2.2. Results & discussion*

Per our pre-registered analysis plan, we converted participants' reproductions into *relative reproduced duration*. Specifically, we computed the proportion of each tone's reproduced duration, relative to the total reproduced sequence length for that trial. This allows us to assess both accuracy and systematic biases. For example, on an equal trial, if participants are accurate, then each tone should be reproduced for approximately 20 % of the total duration; however, if participants systematically overestimate the final tone and underestimate the first tone, then the first tone would consistently comprise less than 20 % of the total duration and the final tone would consistently comprise more than 20 %. The resulting data are plotted in Fig. 1C (note that the data are benchmarked relative to 0.20, such that numbers greater than 0 indicate proportion increases from 0.20 and numbers less than 0 indicate proportion decreases from 0.20). As shown in the figure, participants were roughly accurate: When a tone was shorter than the rest, participants tended to reproduce it as relatively shorter than the rest of the tones (Fig. 1C, left), and vice versa for the longer tones (Fig. 1C, right).

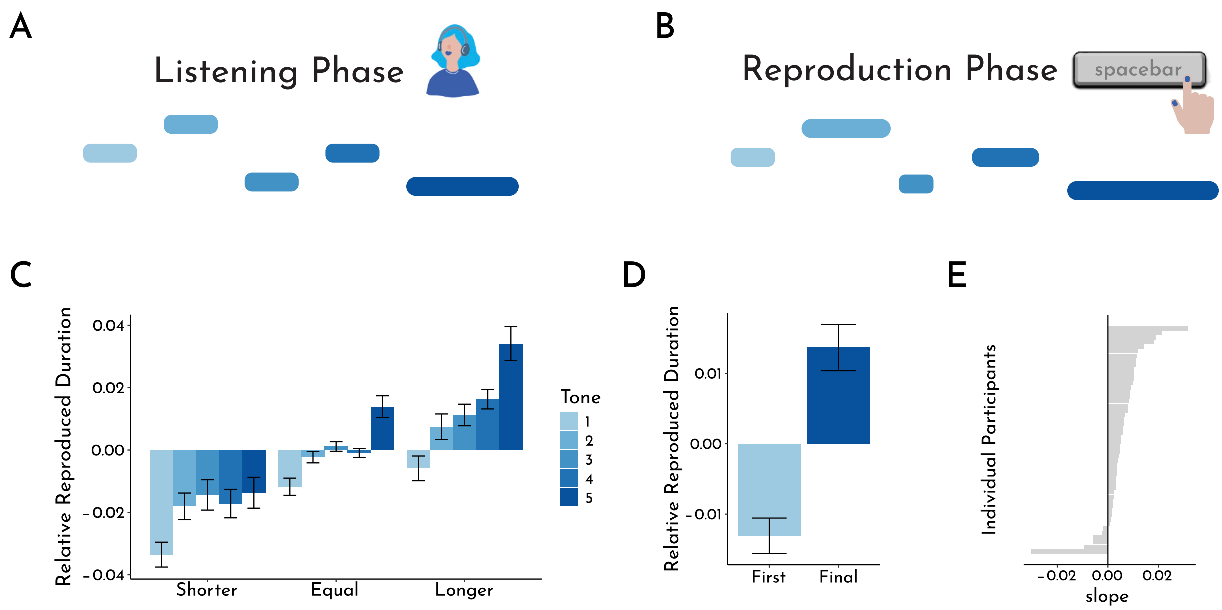


**Fig. 1.** Experiment 1 design and data. A) During the listening phase, participants heard an auditory sequence of five tones, with one tone varying in duration (shorter, longer, or equal to the other four). B) During the reproduction phase, participants reproduced the sequence by holding down on the spacebar on their keyboard. In both A & B, the five horizontal bars represent the tones (tones 1–5, moving left to right). The width of the bar corresponds to the duration of the tone, and the relative height of the bar corresponds to the pitch of the tone. C) We transformed participants' reproductions into 'Relative Reproduced Duration' by dividing each tone's reproduced duration by the total reproduced time for a given trial, giving us a way to compare each tone's proportional reproduced duration to the objective distribution. We plot the average relative reproduced time (across participants) of each tone in the sequence as a function of how much it deviated from 20 % of the total sequence duration (positive values = longer than 20 % of the sequence duration), separately for the trials in which one tone was shorter (left), equal (middle), or longer (right). D) Comparison between the relative reproduced duration of the first and final (fifth) tones, collapsed across all trial types. E) The average slope of reproduced duration across the five tones (each bar represents a participant). In all graphs and figures, error bars represent ±1 SEM.

Notably, there also appeared to be systematic biases based on tone position, as evidenced by an apparent underestimation of the first tone, an overestimation of the final tone, and a continuous expansion of time throughout the sequence.

To characterize these biases, we first assessed whether there was an overall difference in the reproduced duration of first vs. final tones. Collapsing across all trials, we found that the final tones were reproduced as significantly longer than the first tones ($t(49) = 5.15$, $p < 0.001$, $d = 0.73$; Fig. 1D). As a pure test of this effect, we ran this analysis only on the equal trials, when all five tones were the same duration. We still observed this effect ($t(49) = 4.57$, $p < 0.001$, $d = 0.65$), providing strong evidence for this bias even when there were no objective differences in tone duration.

Second, to understand whether there was a continuous change in subjective time across the five tones, we computed the slope across the five relative reproduced durations. Specifically, for each participant, we calculated the relative reproduced duration of each tone (averaged across all trials) and computed the slope across those five averaged durations (Fig. 1E). Across participants, there was a significantly positive slope ($t(49) = 4.55$, $p < 0.001$, $d = 0.64$), indicating that each tone was reproduced, on average, as progressively longer than the previous tone. We again focused in on the equal trials, in which all tones were of equal length. We still observed a positive slope ($t(49) = 4.17$, $p < 0.001$, $d = 0.59$), indicating that this bias emerged even when there was no true difference in tone durations.[1]

Together, these results suggest that people's experience of time within an event does not follow objective duration, but is instead biased by the internal sequential structure — namely, time seems to dilate as an event unfolds. We hereafter refer to this finding as the *event-based temporal distortion.*

[1] To verify that this effect was genuinely task-driven, rather than merely reflecting an intrinsic bias to produce time as increasing across an interval, we ran a control experiment, in which participants were simply tasked with producing the same length tone five times (without a preceding listening phase). We found no evidence for an increasing bias in this case.

## 3. Experiment 2

In Experiment 1, we found evidence that subjective time is systematically distorted based on ordinal position — beginnings were underestimated and endings were overestimated. We sought to replicate and extend these results in Experiment 2. Rather than presenting participants with sequences in which only one tone varied in length, we constructed sequences that were of decreasing, increasing, or equal durations. We were particularly interested in participants' performance on the decreasing trials, in which the objective relative durations directly contrasts our hypothesized pattern of results.

### 3.1. Methods

#### 3.1.1. Participants

Consistent with our preregistered criteria, the final sample size was 50 participants. Based on our pre-registered criteria, 3 individual trials were excluded.

#### 3.1.2. Task design and procedure

The procedure was identical to that of Experiment 1, except that we modified the structure of the sequences (Fig. 2A). Instead of manipulating the duration of one of the five tones in the sequence, each sequence followed one of 5 patterns. The patterns were as follows, with each decimal indicating the proportion of the total sequence duration for which that tone was (e.g., 0.10 = 10 % of the total duration; on a 4-s trial, that tone would be 400 ms): 0.10/0.15/0.20/0.25/0.30 (large ascending); 0.30/0.25/0.20/0.15/0.10 (large descending); 0.14/0.17/0.20/0.23/0.26 (gentle ascending); 0.26/0.23/0.20/0.17/0.14 (gentle descending); 0.20/0.20/0.20/0.20/0.20 (equal). There was a 100 ms

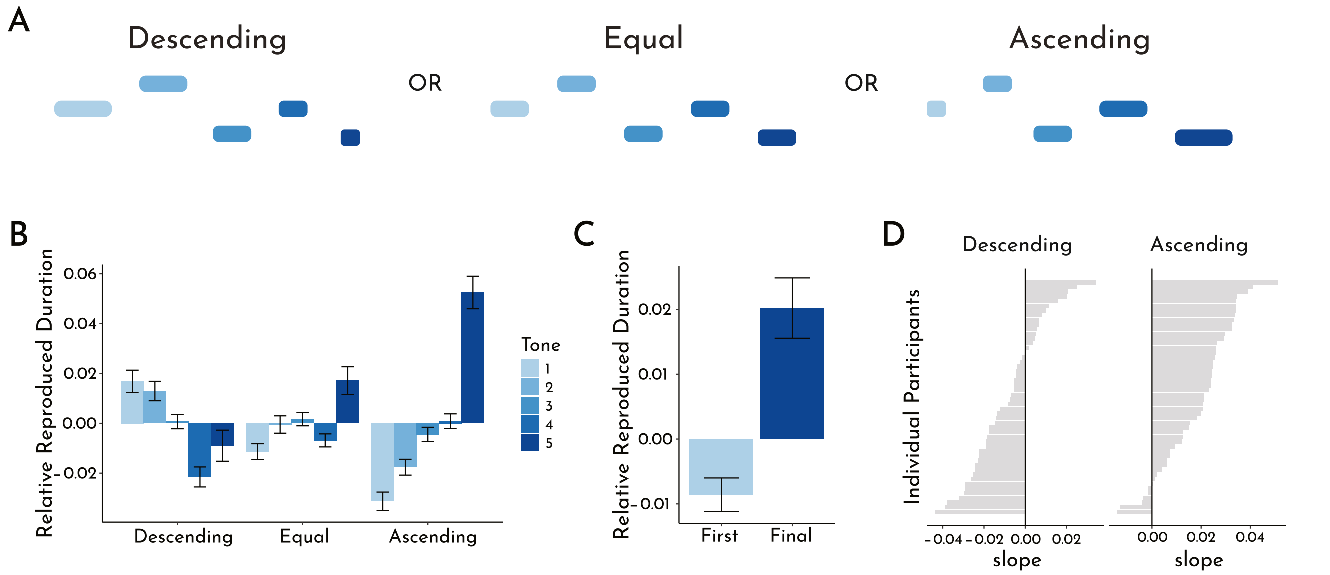


**Fig. 2.** Experiment 2 design and data. A) During the Listening Phase, participants heard different patterns of an auditory sequence of five tones: across the five tones, the durations of each tone decreased (Descending, left), remained equal (middle), or increased (Ascending, right). Participants then completed the same Reproduction Phase as in Experiment 1. B) Relative reproduced duration, separately for the descending, equal, and ascending trials. C) Comparison between the relative reproduced duration of the first and final (fifth) tones, collapsed across all trial types. D) The average slope of reproduced duration across the five tones (each bar represents a participant), separately for the descending (left) and ascending (right) trials.

pause between each tone. We included both the large and gentle ascending/descending sequences to increase the variability in sequence types and tone durations. Each sequence type/sequence duration combination was presented twice (with the exception of the equal trials, which were presented 2× times relative to other sequence types, as in Experiment 1) for a total of 24 trials.

We presented participants with these ascending and descending sequences (rather than manipulating the duration of a single tone, as in Experiment 1) to examine the conjoint influences of the true sequential structure and our hypothesized effect. In Experiment 1, we found that participants judged time to continuously increase throughout the sequence, even when the duration of each tone was equal. By this logic, we may expect this pattern to manifest even more strongly in the sequences with an ascending structure (as there would be additive effects of the true sequence structure along with participants' biased representations of time). In turn, we would also expect a competitive interaction for the descending trials, where duration actually decreases across the sequences: participants may have a bias to perceive time as increasing in length, leading to counteracting effects of the objective duration and our observed event-based temporal distortion.

### 3.2. Results & discussion

As in Experiment 1, we transformed our data into relative reproduced duration before analysis. The data are plotted in Fig. 2B. Participants were roughly accurate in reproducing the ascending and descending patterns. However, there also appeared to be systematic biases based on tone position similar to Experiment 1.

We again tested whether there was an overall difference in the perceived duration of first vs. final tones. Replicating Experiment 1, the final tones were reproduced as significantly longer than the first tones, both when collapsing across all trials ($t(49) = 4.44$, $p < 0.001$, $d = 0.63$; Fig. 2C) and when considering only the equal trials ($t(49) = 3.76$, $p < 0.001$, $d = 0.53$).

We further replicated the finding that there was a continuous increase in subjective time across the five tones. Collapsing across all trial types, there was a significantly positive slope ($t(49) = 3.50$, $p < 0.001$, $d = 0.50$). This again held even when limiting the analysis to equal trials ($t(49) = 2.98$, $p = 0.0044$, $d = 0.42$).

To further probe these effects, we ran targeted analyses on the ascending and descending trials. If participants accurately represent the sequence type, then they should exhibit a positive slope for the ascending trials and a negative slope for the descending trials. However, if the event-based temporal distortion manifests irrespective of sequence type, then participants may exhibit an even greater positive slope in the ascending case and a blunted negative slope in the descending case.

To address this possibility, we first separately assessed the slopes of ascending and descending sequence types (collapsed across gentle and large). There was a significantly positive slope in the ascending trials ($t(49) = 9.07$, $p < 0.001$, $d = 1.28$; Fig. 2D, right) and a significantly negative slope in the descending trials ($t(49) = -3.51$, $p < 0.001$, $d = -0.50$; Fig. 2D, left), suggesting that participants correctly represented the ascending trials as increasing in duration and the descending trials as decreasing in duration.

We next compared the magnitudes of the slopes across the ascending and descending trials to test for our hypothesized interaction between sequence type and the event-based temporal distortion. We predicted that the positive slope in the ascending case would be greater in magnitude than the negative slope in the descending case. To assess this, we flipped the sign of the slope in the descending case and compared the ascending and descending sequences. We flipped the sign, rather than computing absolute value, as taking the absolute value would reduce sensitivity to cases where participants' responses differ from the anticipated trend (e.g., if a participant exhibits a positive slope on a descending trial).

There was a significant difference between the slopes for the ascending and descending trials ($t(49) = 3.23$, $p = 0.0022$, $d = 0.46$), such that the magnitude of the positive slope in the ascending case was greater than that of the negative slope in the descending case. In other words, these data indicate that there was a relative blunting of the negative descending slope, suggesting that the event-based temporal distortion partially counteracted the objective structure of the sequence.

Thus, even when participants were given ordinally structured sequences, systematic distortions persisted — beginnings were underestimated and endings overestimated. The progressive positive slope observed across tones (particularly in the equal-duration condition) and the blunted slope in the descending condition, provides strong support that our sense of time dilates as an event unfolds.

## 4. Experiment 3

Might the temporal dilation we observed in Experiments 1 and 2 be explained not by event structure per se, but by primacy or recency biases? In other words, perhaps the final tone is reproduced as longest because it is the most recent and thus the most salient in participants' working memory. In a third experiment, we addressed this possibility by asking whether the effects persist even when the final tone is not necessarily the most recent tone. We assessed this by having participants listen to two sequences and subsequently reproduce one of the two.

### 4.1. Methods

#### 4.1.1. Participants

Consistent with our preregistered criteria, the final sample size was 50 participants, after excluding and replacing 3 participants. 12 individual trials were excluded.

#### 4.1.2. Task design and procedure

The procedure was identical to that of Experiment 2, with the following change: instead of hearing one five-tone sequence, participants heard two discrete five-tone sequences, separated by a two-second pause (Fig. 3A). To emphasize the differences between the two sequences, one sequence was 4 s in duration and the other was 8 s, and the pitch order was shuffled for each sequence. After hearing both sequences, participants were asked to reproduce either the first or the second of the two sequences (Fig. 3B). Participants did not know in advance which sequence they would be asked to reproduce.

All variables (hearing the 8 or 4 s sequence first, tested sequence type, and whether the first or second sequence was tested) were counterbalanced across 24 total trials. The sequence not selected for reproduction was randomly chosen from the five patterns.

### 4.2. Results & discussion

We first replicated the results of Experiment 2, collapsing across whether the first or second sequence was tested. There was a significant difference in the relative reproduced duration of the first vs. final tones ($t(49) = 4.82$, $p < 0.001$, $d = 0.68$), with the final tones reproduced longer than the first tones. The same held for equal trials ($t(49) = 3.30$, $p = 0.0018$, $d = 0.47$). Additionally, the slope across the five reproduced durations was significantly positive ($t(49) = 4.03$, $p < 0.001$, $d = 0.57$), even when only considering equal trials ($t(49) = 3.18$, $p = 0.0026$, $d = 0.45$). Grouping by ascending and descending trials, we observed a

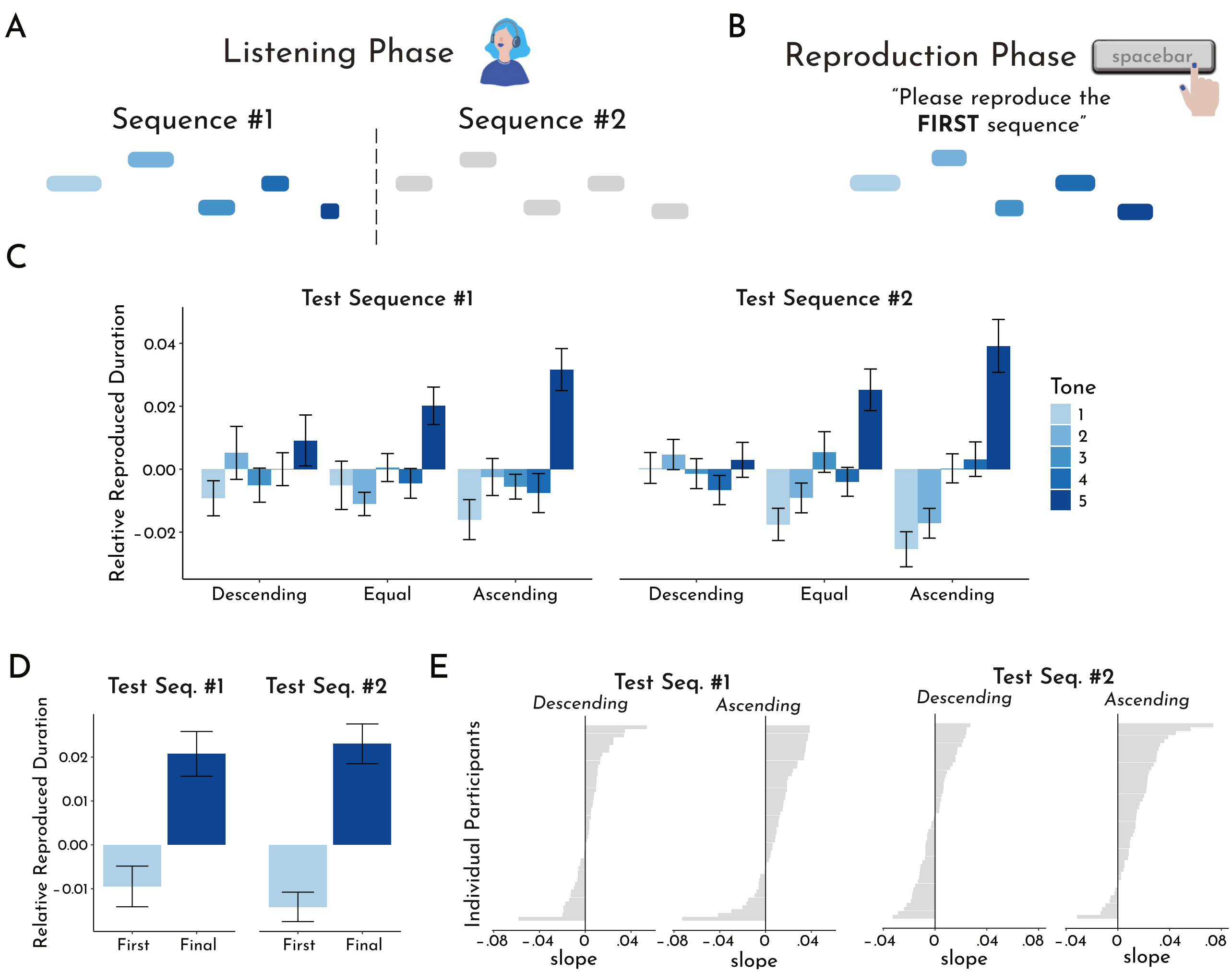


**Fig. 3.** Experiment 3 design and data. A) During the Listening Phase, participants heard 2 sequences of five tones (each following the same patterns as Experiment 2; ascending, descending, or equal) separated by a two-second pause. B) During the Reproduction Phase, participants were asked to reproduce either the first or second sequence (they did not know in advance which would be tested). C) Relative reproduced duration across trial types, separately for the trials in which the first sequence was tested (left) or the second sequence was tested (right). D) Comparison between the first and fifth tones for the three trial types, collapsed across all trials, separated by which sequence was tested. E) The average slope of the five durations across all trials for each participant (each bar represents a participant), separately for the descending and ascending trials, and separated by which sequence was tested.

significantly positive slope in the ascending case ($t(49) = 4.98$, $p < 0.001$, $d = 0.70$) and, surprisingly, a non-significant positive slope in the descending case ($t(49) = 0.71$, $p = 0.48$, $d = 0.10$), resulting in a significant difference in magnitude after flipping the sign for the descending trials ($t(49) = 3.83$, $p < 0.001$, $d = 0.54$). Critically, the slope of the descending trials being numerically positive — the reverse of objective tone durations — suggests that the event-based temporal distortion strongly contributes to participants' subjective experience of time.

We next focused our analyses on separately analyzing the data according to which sequence was tested. We were particularly interested in the trials in which the first sequence was tested: If the event-based temporal distortion is simply due to recency (with the most recent tone judged as longest), then we would expect to see our hypothesized effects only when the second sequence was tested. However, if we observe the same effects when testing the first sequence, this would suggest that the event-based temporal distortion may genuinely be driven by each sequence's internal structure (with each beginning contracted and each ending expanded).

Although the data are somewhat noisier than the prior experiments (as would be expected with the added memory demands of hearing and reproducing two sequences), we critically observed the same pattern of a continuous dilation of time — regardless of which sequence was tested (Fig. 3C).

When focusing on the trials in which the first sequence was tested, we replicated the finding that final tones were reproduced as longer than first tones, both for all trials ($t(49) = 3.49$, $p = 0.0010$, $d = 0.49$; Fig. 3D, left) and for equal trials only ($t(49) = 2.08$, $p = 0.042$, $d = 0.29$). We also observed a positive slope both collapsing across all trials ($t(49) = 2.73$, $p = 0.0089$, $d = 0.39$) and when only considering equal trials ($t(49) = 2.13$, $p = 0.038$, $d = 0.30$). Lastly, when assessing the slopes of the ascending and descending trial types, we again observed a significantly positive slope for the ascending trials ($t(49) = 2.95$, $p = 0.0049$, $d = 0.42$), a non-significant positive slope for the descending trials ($t(49) = 1.32$, $p = 0.19$, $d = 0.19$; Fig. 3E, left), and a significant difference between the magnitudes of the slopes of the two trial types ($t(49) = 2.63$, $p = 0.011$, $d = 0.37$). Critically, the fact that we find evidence for the event-based temporal distortion, even when participants are tested on the first sequence (and, importantly, participants do not know in advance which sequence will be tested), suggests that the observed biases are indeed due to internal sequence structure, and not merely due to recency.

We found that the pattern of results was nearly identical for trials in which participants were asked about the second sequence. We replicated both the significant difference between the first vs. final tones (All trials: $t(49) = 5.52$, $p < 0.001$, $d = 0.78$, Fig. 3D, right; Equal trials only: $t(49) = 4.31$, $p < 0.001$, $d = 0.61$) trials, and the positive slope across tones (All trials: $t(49) = 5.06$, $p < 0.001$, $d = 0.72$; Equal only: $t(49) = 3.90$, $p < 0.001$, $d = 0.55$). Separating out the ascending and descending trials, we observed a significant positive slope for the ascending trials ($t(49) = 5.85$, $p < 0.001$, $d = 0.83$) and a non-significant negative slope for the descending trials ($t(49) = -0.29$, $p = 0.77$, $d = -0.041$; Fig. 3E, right). There was still a significant difference between the magnitudes of the ascending vs. descending slopes ($t(49) = 4.15$, $p < 0.001$, $d = 0.59$).

As a final test of whether the current findings can be explained by recency, we ran a non-preregistered analysis in which we compared the total reproduced durations across the first vs. second sequences (summing the reproduced durations of the five tones). If recency biases temporal duration judgments to be longer, then we may expect the overall reproduced duration to be longer on trials for which the second sequence was tested. Although the reproductions of second sequences were numerically longer, the difference was not significant ($t(49) = 1.54$, $p = 0.13$, $d = 0.22$).

By introducing a second, potentially interfering sequence, this design enabled us to test whether the event-based temporal distortion observed in Experiments 1 and 2 reflected simple primacy or recency biases, or instead, whether the effect manifested as a function of each sequence's internal event structure. The persistence of consistent temporal distortions — even for the first sequence, despite its greater temporal distance from the reproduction phase — argues against a simple recency explanation and suggests that the subjective expansion of time across a sequence is grounded in the structure of an event itself.

## 5. Experiment 4

In a fourth and final experiment, we assessed the event-based temporal distortion using a different paradigm. Instead of asking participants to reproduce the sequence, we tasked them with selecting which tone (in a sequence of three tones) differed from the others. We then assessed whether the same biases (e.g., underestimation of first tones and overestimation of final tones) would emerge in this force-choiced manner.

### 5.1. Methods

#### 5.1.1. Participants

Consistent with our preregistered criteria, we obtained a final sample of 50 participants, after exclusions and replacements. Participants were excluded only if (a) they failed to complete the task (e.g., they did not complete all the trials), (b) their responses revealed overt negligence or inattention (e.g., they selected the same choice on 80 % of trials), or (c) they revealed some significant misunderstanding of the task. Under these criteria, we excluded and replaced 8 participants.

#### 5.1.2. Task design and procedure

Experiment 4 was administered similarly to Experiments 1–3, except we replaced the reproduction phase with a forced-choice response phase. Participants were informed that they would hear a sequence of tones and then make judgments on the tones.

During the listening phase, a sequence of three tones was played, and participants were instructed to listen carefully to the tones (Fig. 4A). The tone sequences had a total duration of either 3.5 s or 7 s, and each tone played in one of three pitches ("A4", "A5", or "E5") randomly assigned to the different temporal positions (with the constraint that no two tones of the same pitch will play successively). There was a 100 ms pause between each tone. On a quarter of the trials, all three tones were of each length. On the other three-quarters, one tone differed from the others in duration, varying by ±10 %, ±20 %, or ± 30 %, while the other two tones were of equal length. (As in the other experiments, there were twice as many equal trials as, e.g., +20 % trials, to account for the fact that equal trials are not bidirectional.). We opted for a sequence of three tones, rather than the five-tone sequences used in Experiments 1–3, to make the task manageable for participants (i.e., to reduce the working memory demands) and to reduce the number of combinations necessary for full counterbalancing.

After the listening phase, participants underwent the response phase, in which they were asked one of four questions (unknown to the participants in advance of the trial): which tone was the longest, which tone was the shortest, which tone had the highest pitch, or which tone had the lowest pitch (Fig. 4B). Pitch judgments were included to make the task slightly more variable and to reduce participants' explicit attention to time. Our primary interest, however, was in responses to duration-based trials (i.e., the longest and shortest tone judgments). Participants selected their response by pressing the 1, 2, or 3 key on the keyboard, corresponding to their chosen tone. Participants were only asked about the longest tone on trials where one tone was objectively longer than the others (or of the same length), and likewise for shortest tone trials. We did not enforce any response deadlines during the judgment phase. All variables (tone position, sequence duration, degree of duration deviance, and question type) were fully counterbalanced across 96 trials.

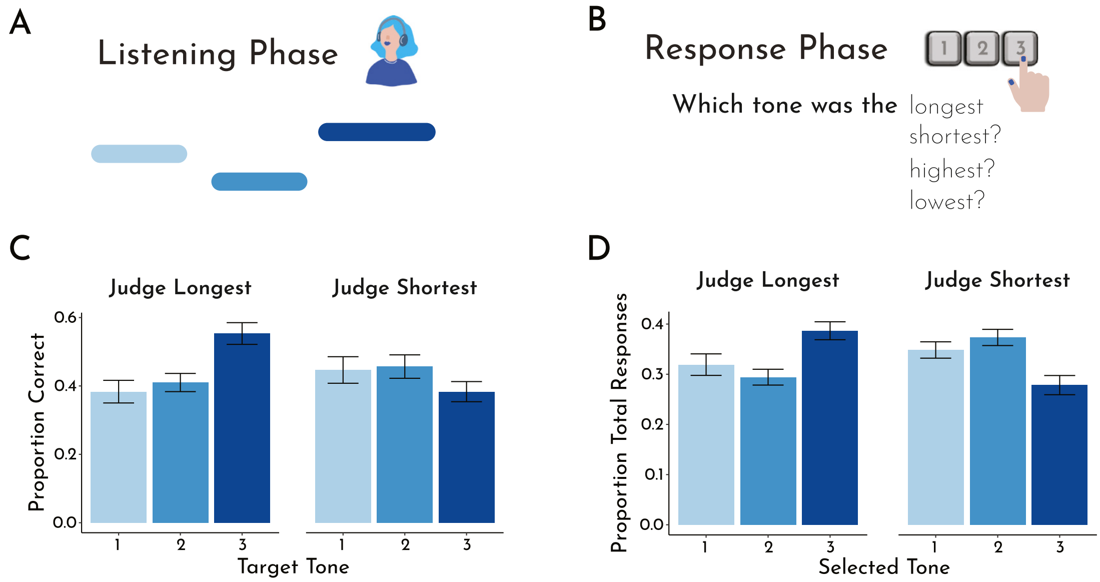


**Fig. 4.** Experiment 4 design and data. A) During the listening phase, participants heard an auditory sequence of three tones, with one tone varying in duration (shorter, longer, or equal to the other two). B) During the response phase, participants made a judgment on the tones (based on the question being asked; either which tone was the shortest, longest, highest pitch, or lowest pitch) by pressing either 1, 2, or 3 on their keyboard. C) Accuracy of participants' choices when asked to judge the longest (left) and shortest (right) tone. D) Proportion of participants' choices (regardless of accuracy) when asked to judge the longest (left) and shortest (right) tone.

### 5.2. *Results & discussion*

To probe the event-based temporal distortion in this forced-choice paradigm, we first assessed whether accuracy (proportion correct) differed as a function of whether the first/second/third tone was the outlying tone. Given our previous findings, we predicted that there would be a bias to judge the final tone as being the longest and the first tone as being the shortest. We excluded the equal trials from this analysis, as there was no objectively correct answer for those. As can be seen in Fig. 4C, there appeared to be systematic biases based on tone position, largely mirroring the pattern of results we observed with the reproductions in Experiments 1–3.

Focusing in on trials where participants were asked to choose the longest tone (judge-longest-tone trials), we observed a significant effect of target tone on accuracy ($F(2, 98) = 9.07$, $p < 0.001$, $\eta_p^2 = 0.16$). Specifically, participants were most accurate when the third tone was the longest, with significantly greater accuracy for the third tone, relative to both the first ($t(49) = 3.65$, $p < 0.001$, $d = 0.52$) and second ($t(49) = 3.57$, $p < 0.001$, $d = 0.51$) tones; there was no difference in accuracy for first vs. second tones ($t(49) = 0.64$, $p = 0.53$, $d = 0.090$). In contrast, we did not observe an effect of target tone on accuracy for the judge-shortest-tone trials ($F(2, 98) = 1.57$, $p = 0.21$, $\eta_p^2 = 0.031$), though numerically, participants were least accurate for the third tones (consistent with the bias that final tones would be judged as longer).

Second, we ran a complementary analysis, but on the overall proportion of responses (regardless of accuracy). In other words, we asked whether the frequency of participants' longest/shortest responses differed for the first/second/third tones. The resulting data are plotted in Fig. 4D, which shows similar systematic biases to the accuracy data.

Mirroring what we observed in the accuracy data, there was a significant main effect of target tone on response choices for the judge-longest-tone trials ($F(2, 98) = 4.45$, $p = 0.014$, $\eta_p^2 = 0.083$), with the third tone selected as longer significantly more than the second tone ($t(49) = 3.55$, $p < 0.001$, $d = 0.50$) and marginally more than the first tone ($t(49) = 1.86$, $p = 0.068$, $d = 0.26$); there was no difference in the proportion of times the first vs. second tone were selected to be longer ($t(49) = 0.75$, $p = 0.45$, $d = 0.11$). There was also a significant main effect of target tone for the judge-shortest-tone trials ($F(2, 98) = 5.43$, $p = 0.0058$, $\eta_p^2 = 0.10$). The third tone was significantly *less* likely to be rated as shorter, relative to both the first ($t(49) = 2.21$, $p = 0.032$, $d = 0.31$) and the second tone ($t(49) = 3.02$, $p = 0.0040$, $d = 0.43$); again there was no significant difference between first and second tones ($t(49) = 0.95$, $p = 0.345$, $d = 0.13$).

We also ran this analysis separately only on the equal trials to determine whether participants show these systematic biases even when no actual difference exists. The likelihood of rating a given tone as longer was not influenced by tone position, $F(2, 98) = 0.89$, $p = 0.41$, $\eta_p^2 = 0.018$. However, we did observe a significant bias in participants' judgments of the shortest tone, $F(2, 98) = 4.44$, $p = 0.014$, $\eta_p^2 = 0.083$. Follow-up tests revealed that participants were least likely to rate the third tone as the shortest, compared to both the first ($t(49) = 2.85$, $p = 0.0064$, $d = 0.40$) and second ($t(49) = 2.24$, $p = 0.029$, $d = 0.32$) tones; there was no significant difference in the likelihood of rating the first vs. second tone as shortest ($t(49) = 0.38$, $p = 0.70$, $d = 0.054$). This bias away from rating the third (and final) tone as shorter is again consistent with the event-based temporal distortion that we observed in Experiments 1–3.

Finally, to verify that these results were not an artifact of a more general bias to select the first/second/third option, we checked whether there were systematic biases in responses to the pitch trials. There were none for either the highest ($F(2, 98) = 0.92$, $p = 0.40$, $\eta_p^2 = 0.018$) or lowest pitch ($F(2, 98) = 0.66$, $p = 0.52$, $\eta_p^2 = 0.013$) trials.

These results largely align with and extend our findings from Experiments 1–3. Specifically, we found converging evidence for the event-based temporal distortion even in a forced-choice paradigm with minimal working memory demands and brief tone sequences. This effect was primarily driven by the final tone: Participants were more likely to judge the final tone as longer and less likely to judge the final tone as shorter. Although we did not observe strong effects for the first tone (we hypothesized that the first tone should also be more likely to be judged as shorter), we note that reducing the sequence length to three tones may have limited our ability to detect differences across the sequence, perhaps making the beginnings less salient. We also found that the effects for the equal trials were more variable (i.e., an effect for 'shortest' judgments, but not 'longest') compared to the robust results that we observed for equal trials in Experiments 1–3. Again, this may be an artifact of the forced choice paradigm. First, by reducing to three tones (which we did to minimize task difficulty), it may be more salient to participants that the tones are in fact equal. Second, by tasking participants with making a discrete, explicit judgment (of what is longer/shorter), we reduced our sensitivity to detect more subtle distortions which were present via reproduction. Nevertheless, we see the current results as providing converging evidence for the event-based temporal distortion.

## 6. General discussion

In the current study, we find that the experience of time is distorted with respect to the internal structure of events. At least on the short timescales tested here, beginnings appear to be represented as relatively *shorter*, endings appear to be represented as relatively *longer*, and there seems to be an increasing expansion of time as an event unfolds. We observed this pattern of results in both reproduction tasks (Experiments 1–3) and forced-choice tasks (Experiment 4). Critically, we also showed that these effects are unlikely to be explained by primacy/recent effects (since they emerge for distinct, back-to-back events; Experiment 3). All together, these results offer a glimpse into how memory for time may be shaped not only by structure *across* events, but also by structure *within* events.

### 6.1. Temporal memory and events

How do we remember *when* something occurred? You can probably effortlessly recall the lasting sporting event you attended, but (depending on how long ago that was) you may have to think for a moment to recall exactly when that was. This common experience reveals an obvious truth: Our memories aren't encoded with "timestamps". We instead have to reconstruct our mental timelines using various context clues and heuristics (see, e.g., Sherman & Yousif, 2025).

The present results indicate one of many factors that may distort our sense of when things occurred: its position *within* an event. Our focus on the *internal* structure of an event is distinct from prior work, which has focused on the structure *across* events (e.g., Ezzyat & Davachi, 2014; Sherman et al., 2023; Yates et al., 2023). That is, prior work has shown that boundaries *between* events cause distortions of temporal memory; here we show that the internal structure of an event itself (its beginning, middle, and ending) also distorts represented time.

On the surface, some of our results could be construed as a generic effect of primacy/recency, rather than a genuine effect of event structure. In other words, perhaps more recently encountered information is simply remembered as longer, irrespective of event structure. However, the results of Experiment 3 speak against this interpretation. In Experiment 3, participants heard two sequences of five separate tones, one after the other. Critically, we observe the same effects of beginnings and endings regardless of whether we probe the first or second sequence. By showing that these effects emerge for two independent events, experienced one after the other, we rule out the possibility that more *recent* things are remembered as longer and more *distant* things are remembered as shorter; rather, the results suggest that these effects operate at the level of individual events.

By characterizing the influence of internal event structure on representations of time, our work speaks to an important quality of events: They are not just moments that occur one after another, separated by stark boundaries. Events are structured entities that are nested into other structured entities, hierarchically. A series of actions comprise a single event (e.g., making coffee, preparing eggs, and eating comprise the "breakfast" event); a series of unique events combines to create one larger event (e.g., eating breakfast, commuting to work, and having your first meeting might comprise a more general "morning" event); and several larger events can combine to fill an entire day. In other words, events are *hierarchical* (see Yates et al., 2023). Although our current findings do not directly speak to the influence of such hierarchy on representations of time and memory, we see our current results as a step towards studying the hierarchical nature of events. Specifically, each tone within the five-tone sequences we presented could be considered a "subevent" which together comprise the "event" which is the sequence. Thus, the paradigm presented here offers a template for how future work may study event hierarchy (i.e., by manipulating structure both within and across events).

### 6.2. Temporal dilations and contractions within and across events

Our findings are notable not only in that they show an effect of internal event structure on representations of time, but also in that they show distinct distortions for beginnings and endings (beginnings compressed and endings expanded).

To this end, our work complements previous work suggesting that time *around an event boundary* can be uniquely contracted and dilated. Specifically, Ongchoco et al. (2023) use a rhythmic reproduction task in which participants are tasked with reproducing the spacings between tones (in contrast to the current study, in which participants are tasked with reproducing the durations of the tones themselves). They find that time prior to an event boundary is 'sped up', such that tones were reproduced too early in time, and tones immediately following an event boundary were delayed (played too late in time). Although our current study is not directly comparable to theirs (especially given that their focus was on event boundaries, whereas ours was on internal structure), it is notable that both studies find non-uniform distortions of time depending on sequential structure. Future work may seek to unify these findings and understand whether these distortions may simultaneously emerge in a task which contains a hierarchical sequential structure.

Our findings may also be related to other literature on how the presence of an event influences representations of time and memory. For example, Goh et al. (2025) recently demonstrated the phenomenon of *Event-Based Warping*, wherein two moments within an event are judged as further apart in time than two moments which are not bound by an event. Critically, however, Event-Based Warping would not account for the unique distortions of beginnings and endings of events. That said, recent work on Object-Based Warping (the object-based analog of Event-Based Warping) has suggested that space can be differentially expanded or contracted within vs. near the bounds of an object (Lebed et al., 2023; Vickery & Chun, 2010). Whether and how this may play out in the time domain (leading to distinct contractions of beginnings and expansions of endings) is unclear.

Finally, the differential effects of compression for beginnings and expansion for endings may be related to the idea of *Representational Momentum*, in which continuously evolving events are remembered to have changed more than they actually did (e.g., participants remember an ice cube as more melted than it actually was; Hafri et al., 2022). Although these are effects of memory, they could be construed as effects of time: participants may be temporally extending their memories beyond what actually occurred. Interestingly, Hafri et al. (2022) also found some evidence for the opposite effect early on within the event. That is, participants misremembered moments from early in the event as having occurred *even earlier* (e.g., an ice cube just starting to melt is misremembered as a fully intact ice cube), suggesting that there may also be temporal compression of the beginning of the event. Thus, these findings raise the intriguing possibility that representational momentum within an event could result in the event-based temporal distortions observed here.

### 6.3. Biases of perception or memory? The El Greco fallacy and temporal reproduction

El Greco was an artist during the Spanish Renaissance, regarded as one of the greatest talents of his generation. His paintings had one distinctive feature: an exaggerated, elongated style, such that subjects appeared thinner and taller than in reality. At one point, it was theorized that this style may have resulted from a particular extreme case of astigmatism, distorting his perception of the visual world. Herein lines the fallacy: If El Greco perceived the world as elongated, wouldn't he also perceive the canvas on which he painted as similarly elongated? If so, wouldn't the elongated bias of perception and the elongated bias of production (i.e., on the canvas) cancel each other out? This "El Greco fallacy" is not just a matter of debate for art historians; in recent years, it has been used to describe various interpretive challenges in experimental cognitive science (see, e.g., Firestone & Scholl, 2014; Chituc & Scholl, 2025).

Our reproduction experiments (Experiments 1–3) introduce the same ambiguity. Suppose, for instance, that people *perceive*, in the present moment, endings to be longer than beginnings. As they experience any given sequence of tones, they literally perceive the final tone(s) as longer than the initial one(s). But when they go to reproduce that sequence, the same should be true: If the ending feels longer at the time of reproduction, then participants should actually hold the button down for *less* time. The effects should cancel each other out.

For this reason, it is difficult to discern whether the reproduction results reflect the *perception of time,* the *recollection* of time, or some combination of the two. If the perception of time is veridical, but the *memory* of time is distorted, then the effects that we observe can be interpreted straightforwardly. Another possibility is that there is a genuine distortion of perception which we cannot detect (because they cancel each other out), but that there is an additional distortion of memory producing the detectable effect. There's no way of knowing, from the data themselves, which of these things is true. We think this should be treated not as an insurmountable obstacle in the study of temporal memory/perception, but as a unique challenge to overcome. Indeed, this challenge is not one faced by the present work alone: Numerous other papers using reproduction methods face the same interpretative challenge (see, e.g., Barkley et al., 2001; Grondin, 2010; Liverence & Scholl, 2012; Mioni et al., 2016; Ongchoco et al., 2023).

There are two reasons that we believe these results are meaningful, in spite of this challenge. First, we clearly find that represented time is distorted with respect to event structure *somehow*. Thus, these results contribute to our understanding of the relationships between time, memory, and event structure. Second, we find converging evidence from a forced-choice paradigm. Although the forced-choice paradigm on its own is a bit contrived, the converging evidence from these (very) different paradigms builds confidence that the patterns we observed here are robust (at least on this timescale).

### *6.4. Beginnings and endings across temporal scales*

In the current study, we found robust evidence that beginnings of events were contracted and endings of events were dilated in time. This might be thought of as a sort of event-based recency effect, such that the endings of events loom larger in working memory, leading to temporal expansion. This result may invoke recent ideas that the endings of events are prioritized in perception and cognition (Ji & Papafragou, 2020; Ongchoco & Scholl, 2019) as well as classic ideas of recency effects in memory (Kahana et al., 2024) and the peak-end rule, in which the endings of experiences are over-weighted in memory (e.g., Varey & Kahneman, 1992). Critically, however, our results are distinct from these prior findings. Our results show not that memory or cognitive processing is enhanced, but that subjective time — at least on the order of seconds — is dilated. Whether and how our current results may be related to or arise from the privileged processing of 'endings' remains to be explored.

We do not take the current results as a universal law of how beginnings and endings influence time perception or temporal memory. There are many known effects of time perception that differ depending on the scale (e.g., event boundaries can lead to an expansion of time in long-term memory, as in Ezzyat & Davachi, 2014, but a contraction of time in short-term or working memory, as in Sherman et al., 2023) and/or context (e.g., Wen & Egner, 2022). Thus, given that the current results emerge on the order of seconds (perhaps within the range of working memory), it is not clear how time perception is shaped by the everyday "beginnings" and "endings" in our lives. Is the beginning of a lecture shorter than the end? What about the first few months of the year? Teigen et al. (2017), for one, argue that at the scale of historical epochs, beginnings are more salient than endings, hinting that perceived time may be distorted in some way as a result (though this was not directly explored). Thus, although we see the current work as an initial case example of how internal event structure can robustly distort time, future work should take care to generalize these results beyond this specific experimental scale/context. For example, future work increasing the length of the delay between the listening phase and reproduction phase (or adding a distracting task between the two), might shed light on whether the present results are dependent on working memory or long-term memory representations. Additionally, lengthening the duration of the sequences themselves would inform our understanding of whether the influence of event structure on time may differ as a function of the duration of the events themselves.

## 7. Conclusion

Virtually every aspect of our experience conspires to distort our sense of time. Here, we have shown that one such aspect is the internal structure of events themselves: Beginnings of events are represented as relatively shorter in duration, and endings of events are represented as relatively longer in duration. These findings open the door to new questions about how beginnings and endings influence perceived time *at the scale of ordinary experience*. Answering those questions may help further our understanding of the deep relationship between perception, memory, and our (ever-changing) sense of time.

## CRediT authorship contribution statement

**Cynthia Wen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sami R. Yousif:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Brynn E. Sherman:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Formal analysis, Data curation, Conceptualization.

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## Data availability

The data are publicly available on our OSF page: https://doi.org/10.17605/OSF.IO/9SEUZ.

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