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The Emotion Filmmaker: Temporal Memory, Time–Emotion Integration, and Affective Style

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Open Science Practices: The present study was preregistered on OSF (https://osf.io/3h8ns), where we detailed how we determined the sample size, the study design and experimental manipulations, main and exploratory hypotheses, the data analysis plan, and all data exclusion criteria. Any discrepancies between the preregistered plan and the analyses in the manuscript were detailed in ***Supplemental Material***. Other materials, including the data, scripts used for running the experiment, and data analysis scripts, can also be found here (https://osf.io/3h8ns).

Abstract

Emotional experiences are temporally dynamic, but prior work suggests that temporal features are usually neglected in remembered emotion. For instance, retrospective emotion evaluations are often biased by discrete salient timepoints, such as the peak and end moments, at the expense of objective event duration (i.e., peak–end effects and duration neglect). However, how these retrospective emotion biases originate, as well as their significance for emotional functioning, remain unclear. Here, we test the hypothesis that retrospective emotion biases are related to fundamental limits of temporal processing and memory capacity. Further, we examine whether these limits have implications for emotional functioning. Participants (n = 60) underwent a novel paradigm comprising affectively-rich movie sequences while providing emotion ratings continuously (moment-by-moment) and retrospectively. Temporal memory for previously-watched emotional-movie sequences and dispositional negativity were measured. Our findings revealed a greater "end" bias as the duration of emotional-movie sequences increased, suggesting that limitations in temporal processing capacity may contribute to retrospective emotion biases. Critically, temporal-memory errors were associated with larger retrospective emotion biases and with individual differences in dispositional negativity. Collectively, these results indicate that retrospective emotion biases may stem partly from mnemonic temporal errors that are emotionally maladaptive.

Keywords: emotion, temporal memory, time–emotion integration, retrospective emotion biases, dispositional negativity

Introduction

Emotional events are usually experienced as a continuous flow, but retrospective emotion evaluations reveal a temporally fragmented and uneven hedonic past. In a seminal study, Fredrickson and Kahneman (1993) uncovered that not all timepoints of emotionally dynamic experiences are weighted equally in retrospective emotion evaluations. Instead, the most intense (*"peak"*) and final (*"end"*) emotional fluctuations are typically weighted more heavily than other timepoints (i.e., the *peak–end effect*). Moreover, the temporal *duration* of emotional experiences plays a seemingly minor role in sculpting retrospective emotion—for instance, prolonging aversive emotional episodes does not necessarily yield corresponding increases in the magnitude of remembered negative emotion (i.e., suggesting *duration neglect*; Fredrickson & Kahneman, 1993). These biases have often been replicated (*peak–end effect*: Asutay et al., 2021, 2022; Chajut et al., 2014; Do et al., 2008; Finn, 2010; Hsu et al., 2018; Kahneman et al., 1993; Redelmeier & Kahneman, 1996; Scheibehenne & Coppin, 2020; *duration neglect*: Redelmeier & Kahneman, 1996; Scheibehenne & Coppin, 2020, but see also: Ben-Zeev et al., 2009; Miron-Shatz, 2009). Nonetheless, despite the robustness of these biases, their underlying mechanisms and implications for emotional functioning remain unclear.

It is possible that temporal memory capacity is inherently limited, giving rise to temporal neglect in remembered emotion. Moreover, prioritized attentional processing of emotional information has been shown to impair the processing of contextual and/or temporal features inherent to the emotional event, such as event duration (Droit-Volet & Gil, 2009). Insights from episodic memory studies further underscore these emotional-temporal processing trade-offs, and indicate that while encoding and retrieval are often prioritized for emotional items, contextual and associative learning can be hindered, including emotional item-temporal context binding as well as temporal binding across items (Bisby et al., 2016; Bisby & Burgess, 2017; Cohen & Kahana, 2022; Mather et al., 2007; Palombo & Cocquyt, 2020; Petrucci & Palombo, 2021; Talmi et al., 2019). Accordingly, a growing literature suggests emotion-driven distortions in temporal memory (for reviews, see Palombo & Cocquyt, 2020; Petrucci & Palombo, 2021). For instance, the remembered duration of negative events is often subjectively dilated, whereby negative events are remembered as longer than they originally were and/or than neutral events (Campbell & Bryant, 2007; Johnson & MacKay, 2019; Loftus et al., 1987; Stetson et al., 2007). Emotional items can also disrupt chronologically organized free recall, producing emotion-driven clustering of items in memory retrieval (Cohen & Kahana, 2022; Talmi et al., 2019). Temporal memory for the order in which events occurred has likewise been found to be altered by high-arousal negative emotion (impaired: Huntjens et al., 2015; Maddock & Frein, 2009; and enhanced: Dev et al., 2022; Riegel et al., 2023; Schmidt et al., 2011).

Collectively, these studies indicate that emotions often sculpt temporal memory, and raise the possibility of a "push-and-pull" dynamic between emotional and temporal memory, whereby preserved temporal memory in the face of emotional events could help mitigate retrospective emotion biases suggestive of temporal neglect. In other words, the capacity to process and remember temporal information associated with emotionally challenging events should reduce retrospective biases that are driven by a few salient moments—and instead promote retrospective evaluations of dynamic emotional experiences that better incorporate temporal information. It is that possibility that we examine in this study: Is high-fidelity temporal memory associated with decreased biases in retrospective emotion judgments? While direct evidence for such an association is lacking, recent data hint at the potential impact of temporal processing capacity limits on how we remember the way that emotional episodes unfolded over time. Asutay et al. (2021) found that the "peak" effect emerged primarily following relatively long emotional-event sequences. Similarly, Goldenberg et al. (2022) identified greater "end" effects following longer emotional-face sequences. However, neither of these studies included measurements of temporal memory *per se*, thereby leaving unclear whether temporal memory fidelity is associated with the magnitude of retrospective emotion biases. Moreover, these studies have largely overlooked how participants' *subjective* emotional feelings are integrated over time—instead using normative emotion ratings as a proxy for momentary emotion (Asutay et al., 2021) or focusing on perceptual—as opposed to experiential—emotion judgments (Goldenberg et al., 2022).

Therefore, in the current study, we obtained momentary and retrospective ratings of subjective emotional feelings in response to dynamic sequences of emotional events—and subsequently measured participants' temporal memory for those events. We hypothesized that high-fidelity temporal memory for dynamic emotional events would serve a protective effect, and be associated with reduced biases in retrospective emotion judgments.

Finally, we sought to uncover the potential functional significance of retrospective emotion biases and putative limits in temporal memory capacity. While limited information processing capacity may make us prone to retrospective memory biases, we posited that persistent overreliance on salient emotional moments when reconstructing one's emotional past—at the expense of accurate, temporally organized emotional memories—could be detrimental to wellbeing (Wang et al., 2022). Indeed, prior insights underscore the importance of considering memory for temporal context when characterizing adaptive emotional responding. For instance, emotion-related impairments in temporal order memory are more pronounced in individuals with higher state anxiety (Huntjens et al., 2015), and individuals with depression show larger temporal non-linearities in their life narratives (Habermas et al., 2008) and lower recall accuracy of daily affect dynamics (Ben-Zeev et al., 2009). Likewise, the recall of traumatic events in post-traumatic stress disorder (PTSD) is often temporally disorganized (Ehlers & Clark, 2000). Therefore, we hypothesized that larger retrospective emotion biases and temporal memory errors would be associated with higher *dispositional negativity* (NA), a trait-like individual difference associated with vulnerability to mood and anxiety disorders (Shackman et al., 2016).

To test these hypotheses, we developed a novel paradigm to estimate retrospective emotion biases following dynamic emotional events—the *Emotional Sequences Task*. In each trial, sequences of movies depicting affectively rich emotional events elicited time-varying pleasant and unpleasant emotional states (Cowen & Keltner, 2017; **Fig. 1a**). The inclusion of movies eliciting both positive and negative emotion permitted us to extend prior work that has primarily examined retrospective emotion biases following events of a single emotional valence (e.g., Asutay et al., 2021; Chajut et al., 2014; Do et al., 2008; Finn, 2010; Fredrickson & Kahneman, 1993; Goldenberg et al., 2022; Redelmeier & Kahneman, 1996). We manipulated the temporal duration and length of negative *vs.* positive movies within each sequence, such that negative-movie duration was longer than positive for half of the sequences. Participants provided continuous (momentary) and retrospective emotion ratings in response to each sequence. After the *Emotional Sequences Task*, participants underwent surprise temporal memory tasks, in which participants' memory for temporal duration (of negative *vs.* positive events) and temporal order were measured for each sequence.

First, we sought to replicate retrospective emotion biases—i.e., peak–end effects and duration neglect—in response to heterogeneous emotional episodes. Building on recent findings and extending them to self-reported emotional experiences (Asutay et al., 2021; Goldenberg et al., 2022), we hypothesized that retrospective emotion biases would increase with longer emotional-episode durations. Next, we examined whether higher-fidelity temporal memory was associated with lower retrospective emotion biases. Finally, we interrogated the functional significance of retrospective emotion biases and temporal memory for emotional functioning by examining their associations with trait dispositional negativity (see **Fig. 2**).

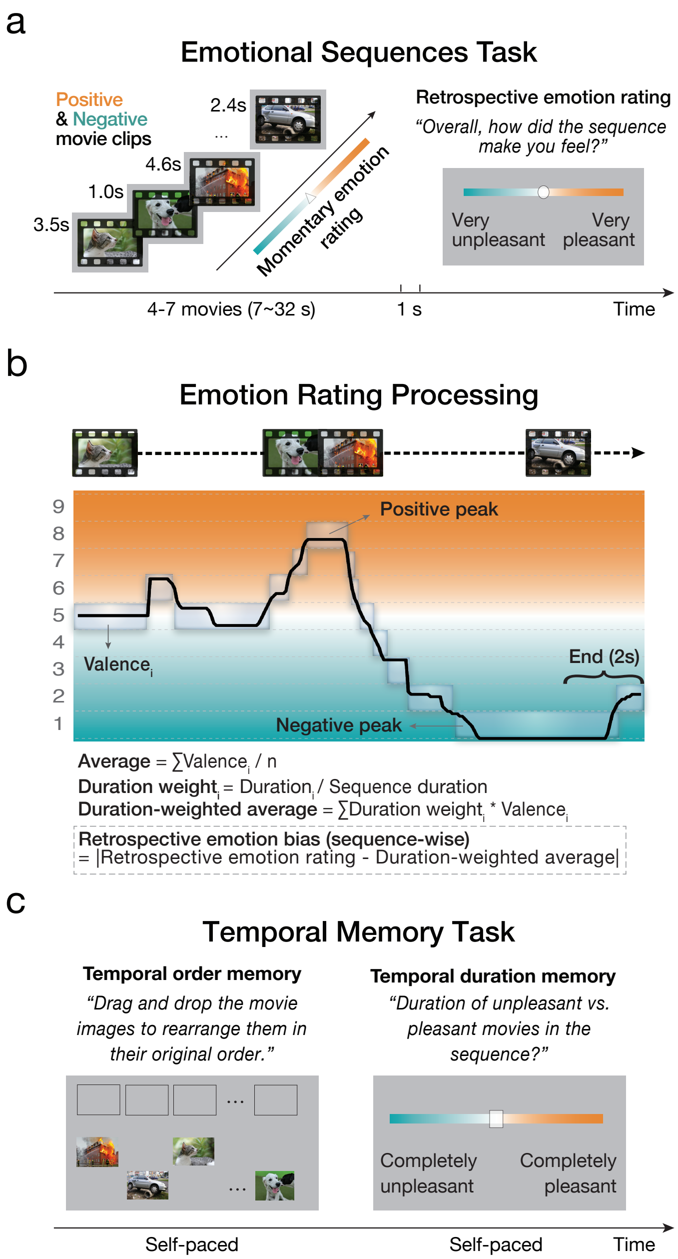

Fig. 1. Experimental design. **(a)** Schematic illustration of task procedures with a representative emotional-movie sequence. In the *Emotional Sequences Task*, participants rated their emotion continuously while watching each sequence (momentary ratings) on a scale from "very unpleasant" to "very pleasant". Following each sequence, they reported a retrospective emotion rating using the same scale. (**b**) Emotional rating metrics are illustrated using data from a trial of a representative participant. The following parameters were extracted from momentary ratings (per sequence): positive peak (the highest rating above the neutral point, i.e., 5 on a 1–9 scale), negative peak (the lowest rating below the neutral point), end (average rating in the final 2s of the sequence), average (average rating), and duration-weighted average (the time weighted-average rating—the duration of each momentary rating refers to the length of time participants stayed at a specific point on the 1–9 scale, and the weight of each rating is determined by its duration relative to the total sequence duration). Sequence-wise retrospective emotion bias was computed as the absolute difference between participants' retrospective emotion rating and the duration-weighted average (i.e., reflecting the rating of an ideal observer who integrates momentary emotion ratings with their temporal durations perfectly to provide a retrospective emotion evaluation). **(c)** After the *Emotional Sequences Task*, participants underwent a surprise memory task—the *Temporal Memory Task*, in which participants indicated, for each sequence, their recollection of movie clip presentation order (order memory) and the relative duration (ratio) of unpleasant (*vs.* pleasant) movies (duration memory). Temporal duration errors in memory were computed as the difference between the recalled vs. actual negative movie duration ratio (to total sequence duration). Temporal order memory accuracy was measured as the Spearman's rank order correlation between the recalled and actual movie order (absolute order memory), as well as the proportion of correctly-ordered pairs out of the maximum number of pairs (relative order memory).

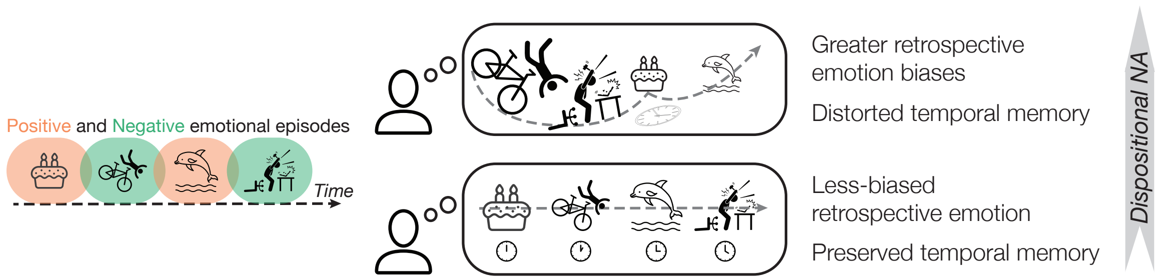

Fig. 2. Conceptual framework of hypotheses tested in this study. Retrospective emotion biases—including peak–end and duration neglect—are well-documented, but their underlying mechanisms and implications for emotional functioning remain unclear. The current study examined whether retrospective biases may stem from limits in temporal memory, and assessed the implications of these biases and temporal memory for trait emotional functioning (here, *dispositional negativity*). Participants watched naturalistic movie sequences designed to produce rich, heterogeneous emotional experiences, and provided continuous as well as retrospective emotion ratings. We predicted that preserved temporal memory following emotional processing would be associated with reduced retrospective emotion biases. Then, retrospective emotion biases and temporal memory errors were examined in relation to trait dispositional negativity to determine the relevance of emotion-temporal interactions for healthy emotional functioning.

Method

Transparency and Openness

This study was preregistered on OSF (https://osf.io/3h8ns). Any discrepancies between the preregistered plan and reported analyses are detailed in *Supplemental Material (see Preregistered vs. reported analysis)*. Other materials, including the data, scripts used for running the experiment, and data analysis scripts, can also be found on OSF (https://osf.io/3h8ns). Below, we report how we determined our sample size, all data exclusions (if any), all study manipulations, and all measures obtained in the study.

Participants

A preregistered sample of n = 80 undergraduates (Age range = 18–29; *M*= 19.91, *SD* = 1.82; n= 54 females) recruited from the subject pool at the University of California, Santa Barbara performed this study via Pavlovia (https://pavlovia.org). Participants were fluent English speakers, with normal or corrected-to-normal vision and no self-reported history of neurological or psychiatric disorders. Twenty participants were excluded from all analyses in accordance with our pre-registered participant-exclusion plan, which followed strict quality control criteria to ensure participant task engagement in this online study (see details in *Data exclusion* below). This resulted in a final sample of n = 60 participants (Age range = 18–29, *M* = 19.88, *SD* = 1.91; n = 41 females). Signed consent was obtained from all participants. All procedures were approved by the Human Subjects Review Committee at the University of California, Santa Barbara. Participants were compensated for their participation with course credit.

We determined our sample size by benchmarking it against the sample sizes used in recent well-powered (power > 80%) laboratory studies on retrospective emotion biases (Asutay et al., 2021: n = 29–49; Asutay et al., 2022: n = 49–54), while ensuring adequate power for individual-difference analyses (see our preregistration for additional details). We also conducted analyses to estimate the sample size needed to replicate retrospective emotion biases, where we assumed a conservative effect size of 0.1 based on recent studies (Asutay et al., 2021, 2022). To compute the sample size required to achieve power over 80% ($\alpha = 0.05$) in our study, we performed power simulations using the "simr" package in R (Green & MacLeod, 2016). We found that n = 25 subjects were required to obtain power > 80% at $\alpha = 0.05$ with the trial number adopted in our study (n = 72). Thus, our final sample (n = 60) was adequately powered.

Data exclusion

Following our preregistered subject-exclusion plan (detailed in https://osf.io/3h8ns), low-quality data were excluded from all analyses. Because the data were collected online, thus precluding close monitoring and observation of the participants, we pre-registered and verified multiple indices of adequate task engagement, as follows. For the emotional sequences task, participant-level data were excluded if participants moved the mouse/trackpad only in the middle 10% of the slider range in 25% or more of the sequences while rating their momentary emotion (the emotion-rating criterion). For the temporal memory task, participant-level data were excluded if they did not try to recollect the movie order during the order memory task—i.e., if did not drag any movie image into a box—in 25% or more of the sequences (the order-memory criterion). Data of n = 10 participants were excluded for not meeting the emotion-rating criterion, n = 2 for not meeting the order-memory criterion, and n = 2 for not meeting both criteria. In addition, n = 6 other data were partially lost and excluded due to technical issues likely stemming from suboptimal internet connection, which resulted in missing values for momentary emotion ratings. Therefore, the final sample used for all analyses reported in the manuscript comprised n = 60 participants.

Materials

Emotional-movie clips and sequences. A pool of n = 396 short movie clips (1-6s) was selected from a well-validated database (Cowen & Keltner, 2017). Half of the movies were positive (M_{Valence} = 6.78, SD_{Valence} = 0.90, M_{Arousal} = 5.86, SD_{Arousal} = 0.89) and half were negative (M_{Valence} = 3.15, SD_{Valence} = 1.08; M_{Arousal} = 5.67, SD_{Arousal} = 0.92). Positive and negative movies were matched on their distance from neutral (valence extremity), $t(394) = -0.76$, $p = 0.45$. The set of n = 396 movie clips was grouped into 2 unique lists of n = 72 movie sequences, with the 2 lists differing in their movie sequence compositions. The presentation order of sequences within a list was randomized across participants. List assignment was randomized across participants. For details, see *Task design: Emotional-movie sequences* in *Supplemental Material*).

Procedure

Emotional sequences task. In the emotional sequences task, participants viewed 72 emotional-movie sequences with varying durations (range = 7–32s, M = 18s) and sequence lengths (i.e., 4, 5, 6, or 7 movies). Following prior work (Fredrickson & Kahneman, 1993; Scheibehenne & Coppin, 2020), participants watched emotional movies while providing continuous ratings of subjective emotion on a scale from "*very unpleasant*" to "*very pleasant*" by moving a mouse/trackpad across a slider. Following each sequence, participants reported a retrospective emotion evaluation: "*Overall, how did the sequence make you feel?*" on a scale from "*very unpleasant*" to "*very pleasant*"; see **Fig. 1a**. (For details, see *Supplemental procedure* in *Supplemental Material*.)

Rating data processing. The following parameters were computed from momentary emotion ratings for each sequence: *positive peak* (the highest rating above the neutral point, i.e., 5 on the 1–9 scale), *negative peak* (the lowest rating below the neutral point)[1], *end* (the average rating in the final 2s of the sequence), *average* (the overall average rating), and *duration-weighted average* (the time weighted-average, where the duration of each rating refers to the length of time a participant stayed at a specific point on the 1–9 scale, and the weight of each rating is determined by its duration relative to the total sequence duration) (see **Fig.1b**; Fredrickson & Kahneman, 1993; Scheibehenne & Coppin, 2020). For instance: in a 6-second sequence with momentary ratings = [3, 6, 9] and ratings' duration vector = [1s, 2s, 3s], $\boldsymbol{Average} = \sum Valence_i/n$ = (3+6+9)/3 = 6; $\boldsymbol{Duration\text{-}weighted\ average}$ = $\sum Duration\ weight_i * Valence_i$ = (1/6)* 3 + (2/6)*6 + (3/6)*9 = 7.

Next, the above-mentioned momentary rating parameters were used to predict retrospective ratings. **Peak–end effects** are evident if positive/negative peak and end significantly predicted retrospective ratings (see *Statistical analysis* for details). **Duration neglect** is evident if the *average* of momentary ratings is a better predictor of retrospective ratings than the *duration-weighted average*.

Of note, raw continuous emotion ratings measured on a 0–100 scale were binned to a 1–9 scale to minimize noise and maximize the reliability of the estimates of momentary emotions and emotional changes, while retaining adequate inter-individual variability. (The 9-point scale was determined using a data-driven approach, which is detailed in *Rating data processing* in *Supplemental Material*). To further ascertain the robustness of our results in relation to the choice of rating scale, we re-analyzed our data using the raw continuous ratings. All of our major results and conclusions were replicated (see *Results on raw continuous emotion ratings* in *Supplemental Material).*

[1] Note: If all ratings for a particular sequence were below or above the neutral point, a missing value was entered for positive or negative peak, respectively, corresponding to 7.38% of positive and 7.26% of negative peaks.

Retrospective emotion biases. We computed trial-wise *retrospective emotion biases* by taking the absolute difference between participants' *duration-weighted average* (i.e., computed from momentary ratings, as detailed above) *minus* their retrospective rating of each sequence (see **Fig.1b**) (Ben-Zeev et al., 2009; Goldenberg et al., 2022). In other words, this retrospective emotion bias metric assumes that an ideal observer integrates dynamically unfolding emotional experiences and their temporal duration without peak- or end-biases; deviations from this ideal pattern therefore suggest retrospective biases.

Temporal memory task. At the end of the experiment, participants completed two temporal memory tasks. We measured memory for the *temporal order* of emotional movie clips and the (relative) *temporal duration* of negative (*vs.* positive) movies within each sequence. In the *temporal order memory* task, participants were shown representative images from previously-watched movies within each sequence (one image per movie) and asked to reconstruct the original movie clip order to the best of their ability. In the *temporal duration memory* task, participants were asked to indicate their recollection of the relative duration of unpleasant (*vs.* pleasant) movies for each sequence, using a slider anchored on "*completely unpleasant*" to "*completely pleasant*" (see **Fig. 1c**).

Temporal memory metrics. To estimate temporal duration memory for each sequence, we computed *temporal duration errors* as the difference between recalled *vs.* actual duration ratio of negative movies to the total emotional-sequence duration (see **Fig. 1c**), which indexed the extent to which negative (*vs.* positive) event durations were dilated in memory (per sequence). For temporal order memory, we computed two trial-wise (sequence-wise) metrics. *Absolute order memory* was calculated as Spearman's rank order correlation between the recalled and actual sequence order (Huntjens et al., 2015; Wegner et al., 1996; Fisher's Z transformed). *Relative order memory* was computed as the proportion of correctly-identified pairwise temporal relationships out of the maximum number of pairwise relationships (Jenkins & Ranganath, 2010).

Mood questionnaires. To derive a *dispositional NA* factor per participant, a principal component analysis (PCA) was conducted using the following self-report mood questionnaires: the *Beck's Depression Inventory* (BDI; Beck et al., 1961), the *State-Trait Anxiety Inventory* (STAI; Spielberger et al., 1983), and the *negative affect* (NA) subscale from the short-form of the *Adult Temperament Questionnaire* (ATQ; Evans & Rothbart, 2007). This analysis was performed using the 'principal' function from the "psych" package in R (Revelle, 2022) to extract the first principal component from the three scales mentioned above. The three scales collectively explained 65.9% of the variance in dispositional NA and all had loadings above 0.70 (λ_STAI = 0.89, λ_ATQ-NA = 0.73, λ_BDI = 0.82).

Statistical analysis

Mixed-effects modeling. We estimated mixed-effects linear regression models using the "lme4" package in R (Bates et al., 2015). By-participant and by-sequence random intercepts were fitted in all models. Random slopes at both levels were also fitted unless their inclusion: (a) resulted in convergence errors, and/or (b) did not significantly improve model fits compared to random-intercept-only models, as indicated by likelihood-ratio tests (Glover & Dixon, 2004)[2]. In cases of convergence errors, we additionally analyzed our data using a Bayesian method that is more tolerant with these errors, which allowed us to further verify the robustness of our models. To that end, we used the "brms" package in R (Bürkner, 2017). All of our conclusions and major results remained consistent when employing the Bayesian models. The *likelihood-ratio test* was used for model comparison whenever the simpler model was nested within the complex model. Otherwise, improvement in model fit was estimated using a Bayes factor

[2] One model (examining the association between temporal duration errors and retrospective emotion biases) included both random intercepts and slopes. The remaining models were random-intercept-only models. Random slopes were omitted from most models due to convergence errors, with the exception of one model (examining the relationship between absolute order memory and retrospective biases) for which the random slope was omitted as its inclusion did not significantly improve the model fit (compared to the intercept-only model).

calculated according to the change in the Bayesian information criterion (i.e., *Bayes ΔBIC*; Scheibehenne & Coppin, 2020; Wagenmakers et al., 2018)[3].

Retrospective emotion biases: hierarchical model comparison. To examine whether participants displayed peak–end and duration neglect biases on average, we fitted mixed-effects linear regression models, as follows (Scheibehenne & Coppin, 2020): First, to examine duration neglect, we tested whether the *duration* of momentary valence ratings predicted retrospective emotion by comparing an *average (rating)* model (m1.1) with a *duration-weighted average* model (m1.2). Duration neglect is evidenced if the average model outperforms the duration-weighted average model (as indicated by Bayes ΔBIC). Next, the winning model was used to examine the "end" effect by testing whether including the "end" rating (m2) further improved the model fit (likelihood ratio test). Then, we tested the "peak" effect by including *positive* and *negative peaks* in the model (m3) and examining whether those factors further explained retrospective ratings and improved the model fit (Bayes ΔBIC). To further determine the import of *peak* and *end* ratings to overall model fits, we additionally tested whether including peak or end ratings significantly improved model fits relative to including a momentary rating from a randomly-sampled timepoint (see *Retrospective emotion: ascertaining specificity of "peak" and "end" contributions* in *Supplemental Material*). Note that all models (here and elsewhere) included the movie list randomly assigned to each participant (short for 'list' below) as a control variable (starting with the baseline model including 'list' only, m0).

Capacity limits of temporal processing and retrospective emotion. To test the hypothesis that retrospective emotion biases increase when temporal processing capacity is challenged, we examined whether *emotional-sequence duration* modulated the strength of retrospective emotion biases. To do so, we tested whether sequence duration interacted with peak or end momentary ratings to predict retrospective emotion ratings (starting

[3] A Bayes ΔBIC comparing model 2 *vs.* 1 is calculated as $BF_{21} = e^{-(BIC_2 - BIC_1)/2}$.

from the winning model as detailed in *Retrospective emotion biases: hierarchical model comparison*). We focused our subsequent analysis on the negative peak given that it explained significant variance in retrospective emotion ratings (see *The peak effect: Negative and positive peaks*) (for related analyses on the positive peak, see *Testing capacity limits: the positive peak* in the *Supplemental Material)*. In addition, given that sequence duration and sequence length (i.e., the number of movies in a sequence) were correlated in the current design, these analyses were also performed using sequence length as a predictor (see *Testing capacity limits: sequence length* in the *Supplemental Material*).

Temporal memory accuracy. Temporal order and duration memory accuracy scores were evaluated against chance using permutation tests (see *Temporal memory accuracy* in *Supplemental Material*).

Temporal order memory and duration memory. To examine potential dissociations between temporal order memory and duration memory, we computed the correlation between temporal duration errors and temporal order memory (absolute and relative metrics) across individuals. See *The dissociation between temporal order memory and duration memory* in *Supplemental Material*.

Association between temporal memory and retrospective emotion biases: trial-wise models. We examined whether temporal memory (temporal duration, absolute and relative temporal order accuracy) predicted retrospective emotion biases using sequence-wise metrics in separate mixed-effects models (see *Mixed-effects modeling* for details). Results of this analysis revealed whether (sequence-wise) temporal memory was associated with retrospective emotion biases, within and across subjects. To reiterate, sequence-wise retrospective emotion biases reflect deviations from an ideal observer irrespective of the specific type of retrospective bias (i.e., whether peak, end, and/or duration neglect). Results obtained using different temporal memory metrics (temporal duration, relative, and absolute order memory) were Bonferroni-corrected for multiple comparisons.

Association between temporal memory and retrospective emotion biases: individual model fit. Next, in order to uncover specific drivers of the association between temporal duration memory and retrospective emotion biases, we correlated individual-level model fits of negative peak, end, and duration neglect models (i.e., model-fit difference scores for models without *vs.* with each of these sources of bias) with temporal memory accuracy across individuals. Specifically, we fit linear regression models including average, duration-weighted average, end, and negative peak models to predict retrospective emotion ratings for each participant. We then computed the difference in individual-model fits (ΔBIC, Bayesian information criterion) between a model that does not include the bias and a model that does (for instance, for the "end" bias: ΔBIC [Average model − End model]). Finally, we correlated model-fit difference scores with temporal memory metrics across individuals. (For details of this approach, as well as results related to the positive peak, see *Associations between temporal memory and retrospective emotion biases: individual model fit* in *Supplemental Material*).

Associations between temporal memory, retrospective emotion biases and dispositional NA. To determine whether temporal memory and retrospective emotion biases were associated with emotional functioning, we correlated dispositional NA with temporal memory metrics as well as with the magnitude of average retrospective emotion biases across subjects. We also correlated dispositional NA with ΔBIC-indexed individual biases. See results in *Associations between dispositional NA and retrospective emotion biases: individual model fit* in *Supplementary Material*.

Results

Retrospective ratings reveal negative-peak and end effects

The end effect. We observed an "end" effect as indicated by the significant fit of "end" momentary ratings in predicting retrospective emotion ($\beta = 0.31$, SE = 0.01, $t = 24.21$, 95% CI [0.29, 0.34], $p < 0.001$). Moreover, adding "end" as a predictor significantly improved the model fit (m2 *vs.* m1.2: $\chi^2(1) = 520.88$, ΔAIC = -518, ΔBIC = -513, ΔLL = 260, $p < 0.001$; See **Table 1** for complete model results). This replicates and extends a plethora of prior work (Asutay et al., 2021, 2022; Chajut et al., 2014; Do et al., 2008; Fredrickson & Kahneman, 1993; Finn, 2010; Hsu et al., 2018; Kahneman et al., 1993; Redelmeier & Kahneman, 1996; Scheibehenne & Coppin, 2020) pointing to the final moments of emotional episodes as critical predictors of retrospective emotion judgments (above and beyond the average emotion experienced during the episode).

The peak effect: Negative and positive peaks. Given recent work indicating that "negative peaks" may disproportionally contribute to retrospective emotion evaluations (Scheibehenne & Coppin, 2020), we investigated whether negative *vs.* positive peaks experienced during emotional-movie viewing differentially predicted retrospective emotion ratings. We found that the inclusion of positive and negative peaks significantly improved the model fit compared to the "end"-only model above, therefore indicating a peak effect (Bayes factor on ΔBIC of m3 *vs.* m2: ΔAIC = -1949, ΔBIC = -1938, BF > 100). Moreover, negative peaks ('troughs') exerted an asymmetric influence on retrospective emotion compared to positive peaks: only *negative* peaks in momentary ratings robustly predicted retrospective emotion judgments ($\beta = 0.14$, SE = 0.03, $t = 4.26$, 95% CI [0.07, 0.20], $p < 0.001$), whereas positive peaks did not ($\beta = 0.03$, SE = 0.03, $t = 0.86$, 95% CI [-0.03, – 0.09], $p = 0.39$; see **Fig. 3a**).

Duration neglect. Averaging mechanisms predicted retrospective emotion from momentary emotion ratings as both the average and the duration-weighted average significantly contributed to retrospective emotion ratings (average: $\beta = 1.04$, SE = 0.03, $t = 32.81$, 95% CI [0.98, 1.10], $p < 0.001$; duration-weighted average: $\beta = 0.88$, SE = 0.002, $t = 41.15$, 95% CI, [0.84, 0.93], $p < 0.001$). Moreover, adding duration weights improved the prediction of retrospective emotion, as revealed by a better fit of the duration-weighted average compared to the average model—thereby underscoring a significant role for the duration of emotional experiences in sculpting retrospective ratings (as opposed to "duration neglect") in our sample (Bayes factor on ΔBIC of m1.2 *vs.* m1.1 favored model m1.2; ΔAIC = -453, ΔBIC = -453, BF > 100).

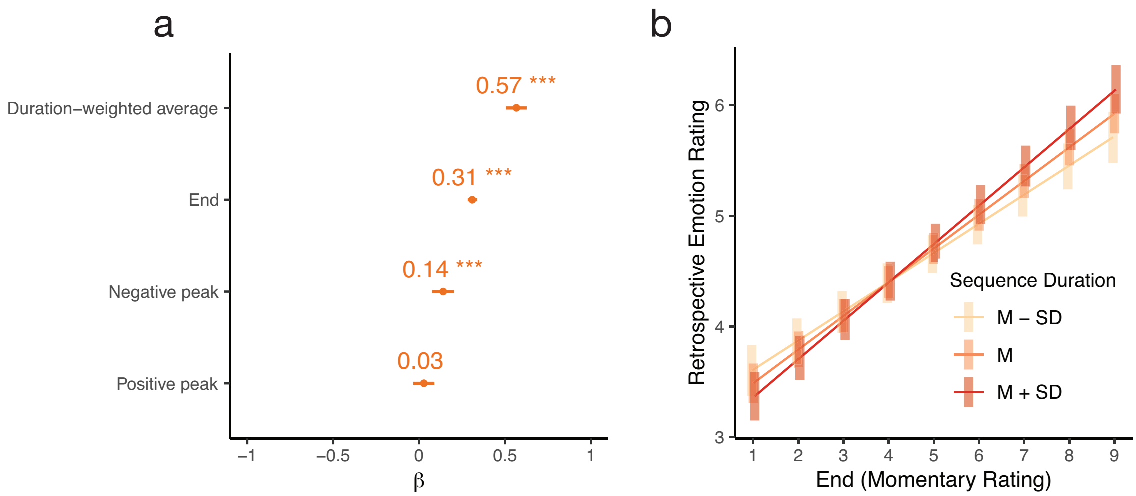

Fig. 3. Retrospective emotion biases: regression models. **(a)** The winning model predicting retrospective emotion ratings indicates peak-and-end effects, but no duration neglect (m3). The peak effect was driven by negative momentary ratings. Fixed-effect estimates (βs) are plotted. **(b)** Retrospective emotion ratings are particularly driven by final ("end") emotional fluctuations when the duration of emotional-sequences increases, suggesting limits in time–emotion integration capacity, which may underlie "end" biases in retrospective emotion judgments (sequence duration by end-effect interaction, $\beta = 0.009$, $p < 0.001$).

The "end" effect increases with sequence duration

Next, we examined whether retrospective emotion biases may emerge as a consequence of limited (temporal) information processing capacity. To do so, we included sequence duration as an interactive regressor in a mixed-effects model predicting retrospective ratings from momentary ratings. We found that longer sequences produced a larger *end* effect, as evidenced by a significant interaction of the "end" term and sequence duration (β = 0.009, SE = 0.003, t = 3.49, 95% CI [0.004, 0.014], p < 0.001; see **Fig. 3b**). Negative peak effects did not differ as a function of sequence duration (β = 0.007, SE = 0.006, t = 1.18, 95% CI [-0.005, 0.02], p = 0.24). In summary, when temporal processing capacity is challenged by longer-lasting events, the final moments of a complex emotional episode are particularly impactful in influencing retrospective emotion judgments.

Temporal duration errors predict retrospective emotion biases.

Duration memory and retrospective emotion biases. As shown in **Fig. 4a**, temporal duration errors, which were driven by a relative dilation of the remembered duration of negative *vs.* positive emotional movies, correlated with larger retrospective emotion biases ($\beta = 0.36$, SE = 0.010, $t = 3.76$, 95% CI [0.15, 0.56], $p < 0.001$). Moreover, including temporal duration errors in a model predicting retrospective emotion biases significantly improved the model fit ($\chi^2(5) = 33.71$, ΔAIC = -24, ΔBIC = 8, ΔLL = 17, $p < 0.001$).

Next, to uncover the primary source(s) of retrospective emotion biases that are associated with temporal duration memory (i.e., whether primarily explained by variance captured by peak–end effects, and/or by duration neglect), we applied an individual-model-fit comparison approach. Briefly, we estimated the extent to which each bias was evident by computing a difference score using individual-model fits (ΔBIC) between a model that did not include the bias and a model that did (e.g., for the "end" bias: ΔBIC [Average model − End model]. Next, we correlated these model-fit delta scores with temporal memory accuracy across individuals (for details, see *Associations between temporal memory and retrospective emotion biases: individual model fit* in *Method* and *Supplemental Material*). Interestingly, although "duration neglect" was not observed at the group level, we found that greater temporal duration errors were associated with larger duration neglect across participants (ΔBIC[Duration-weighted average model – Average model]; $r = 0.46$, $t(58) = 3.93$, 95% CI [0.23, 0.63], $p < 0.001$; **Fig. 4b**). Temporal duration errors were also associated with a *smaller* negative peak effect (ΔBIC[Average model – Negative peak model]; $r = -0.33$, $t(58) = -2.70$, 95% CI [-0.54, -0.08], $p = 0.01$). Given the nature of the difference score we used to compare across models (here, ΔBIC between the average and negative-peak models), this suggests that temporal duration memory errors correlate more strongly with a bias in retrospective emotions towards the average emotion experienced across the entire sequence, rather with the negative peak emotion experienced at a single timepoint. In summary, at the group level, larger errors in remembered emotional-event duration were associated with greater 'duration neglect' (and lower negative peak effects) in retrospective evaluations of dynamic emotional experiences.

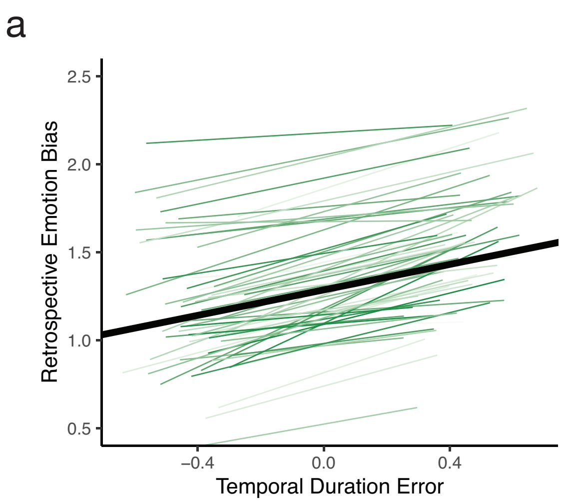

Fig. 4. Temporal duration errors predict retrospective emotion biases. **(a)** Temporal duration errors (i.e., dilation of negative *vs.* positive event duration) in memory correlated with greater retrospective emotion biases within and across subjects, as evidenced by the fit of a mixed-effects model (β = 0.36, p < 0.001), as well as by **(b)** the correlation of temporal duration errors and the magnitude of duration neglect biases in retrospective emotion judgments across subjects (r = 0.46, p < 0.001).

Order memory and retrospective emotion biases. Temporal order memory was not associated with retrospective emotion biases (absolute order memory: β = 0.004, SE = 0.009, t = 0.41, 95% CI [-0.01, 0.02], p > 0.99; relative order memory: β = -0.005, SE = 0.07, t = -0.08, 95% CI [-0.14, 0.13], p > 0.99).

Temporal duration errors are positively associated with dispositional NA.

Individuals with higher dispositional NA showed larger temporal duration errors, which reflected a greater 'temporal dilation' of the remembered duration of prior negative emotional episodes (r = 0.37, t(58) = 3.04, 95% CI [0.13, 0.57], p = 0.004; see **Fig. 5**). By contrast, temporal order memory indices did not correlate with dispositional NA (absolute: $r = 0.12$, $t(58) = 0.89$, 95% CI [-0.14, 0.36], $p = 0.37$; relative: $r = 0.06$, $t(58) = 0.48$, 95% CI [-0.19, 0.31], $p = 0.63$). Average retrospective emotion biases were not associated with dispositional NA ($r = 0.02$, $t(58) = 0.19$, 95% CI [-0.23, 0.27], $p = 0.85$).

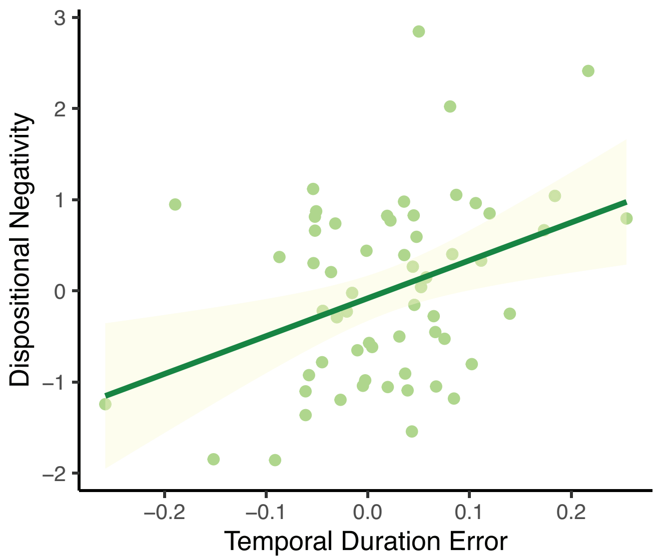

Fig. 5. Temporal duration errors predict dispositional negativity. Individuals with higher dispositional negativity show greater temporal memory duration errors, such that they report greater remembered (*vs.* actual) duration of prior negative emotional episodes (relative to the overall sequence duration; $r = 0.37$, $p = 0.004$).

Discussion

Retrospective emotion biases are pervasive in daily life and robust in the laboratory (e.g., Chajut et al., 2014; Fredrickson & Kahneman, 1993; Redelmeier & Kahneman, 1996; Scheibehenne & Coppin, 2020). Here, we tested the hypothesis that these biases may be related to limits in our temporal memory capacity—and examined the significance of these biases and the quality of temporal memory for emotional functioning. Using emotionally rich, dynamic, and naturalistic emotional-movie sequences (Cowen & Keltner, 2017), we replicated well-documented peak–end effects (Asutay et al., 2021; Chajut et al., 2014; Do et al., 2008; Finn, 2010; Fredrickson & Kahneman, 1993; Hsu et al., 2018; Kahneman et al., 1993; Redelmeier & Kahneman, 1996). Further, we found that recency ("end") biases in retrospective emotion judgments *increased* when temporal processing capacity was challenged by longer-lasting emotional episodes. Critically, emotional sequences associated with temporal duration errors—specifically, with greater temporal dilation of the remembered duration of negative *vs.* positive episodes—produced larger biases in retrospective emotion judgments. Finally, these temporal memory errors were also associated with higher dispositional NA, suggesting their import for everyday emotional functioning. Collectively, these results bridge across the historically separate disciplines of emotional processing and temporal memory to suggest a potential mnemonic origin of biased retrospective emotion judgments.

Here, we investigated whether intra- and inter-individual variation in temporal memory was associated with the magnitude of retrospective emotion biases, putatively reflecting underlying emotion-temporal processing trade-offs (Campbell & Bryant, 2007; Huntjens et al., 2015; Johnson & MacKay, 2019; Loftus et al., 1987; Maddock & Frein, 2009; Palombo & Cocquyt, 2020; Petrucci & Palombo, 2021; Stetson et al., 2007; Talmi et al., 2019; Wang et al., 2022). We found that errors in temporal duration memory indicative of greater dilation of the remembered duration of past negative (*vs.* positive) experiences were associated with larger retrospective emotion biases (within and across individuals). When disentangling the sources of retrospective bias associated with temporal memory using a model-comparison approach, we found that *duration neglect* in retrospective emotional feelings correlated positively with temporal memory errors (across individuals). Prior work points to emotion-related distortions in memory of the duration of episodes—for instance, negative emotional episodes are often remembered as longer-lasting than their objective duration and/or than neutral episodes (Campbell & Bryant, 2007; Johnson & MacKay, 2019; Loftus et al., 1987; Stetson et al., 2007). Our findings suggest a complementary path for how emotion-temporal coding interactions sculpt memory for emotional events: Temporal coding that is resilient to the influence of negative emotional information may help prevent distortions in retrospective emotion judgments. While future research using causal methods is required to fully ascertain the directionality of these emotion-temporal interactions, our results add to a growing literature underscoring the important (and likely bidirectional) interplay between emotion and temporal memory (Cohen & Kahana, 2022; Lapate et al., 2017; Palombo et al., 2021; Palombo & Cocquyt, 2020; Petrucci & Palombo, 2021; Talmi et al., 2019).

Given limited information processing capacity (Marois et al., 2000), biases towards salient moments (such as the 'peaks' and 'ends') in remembered emotion could be a byproduct of selection and prioritization of moments with maximal survival relevance. Accordingly, our results suggest that well-known peak effects are primarily driven by *negative* peaks ('troughs') in dynamic affective experiences as opposed to *positive* peaks. This agrees with a recent finding indicating that negative (*vs.* positive) momentary ratings contribute more strongly to retrospective emotion following exposure to intermixed pleasant and unpleasant odors (Scheibehenne & Coppin, 2020). Evolutionarily, negative information may often have higher survival value than positive information (e.g., a bear in the wild signifying the need to escape) (Baumeister et al., 2001; Norris, 2021; Rozin & Royzman, 2001). Therefore, the privileged status of recent negative experiences over positive ones could be advantageous for remembering cues associated with aversive events, resulting in more effective avoidance when appropriate (Fredrickson, 2000). However, the prioritization of negative *vs.* positive events in memory is likely not without consequences for wellbeing, as prioritizing positive information can help build resiliency (Fredrickson, 2001) and maintain positive self-schemas (Leary, 2007). Whether positivity or negativity biases predominate in memory for emotional experiences likely depends on individual differences in affective style (Norris, 2021), age (Kalenzaga et al., 2016), and context—such as individual's current goals (Kennedy et al., 2004).

Further suggesting that information capacity limits contribute to retrospective emotion biases, retrospective emotion judgments relied more heavily on recent timepoints ('ends') as the duration of emotional sequences increased. This finding aligns with recent studies showing that emotional-sequence length and/or duration can amplify retrospective emotion biases (Asutay et al., 2021; Goldenberg et al., 2022). Here, by adopting dynamic and naturalistic emotional-movie stimuli comprising both positive and negative emotional valences—coupled with high-resolution measurements of self-reported emotion ratings—our study extends previous insights to rich emotional contexts and individualized phenomenology that likely better approximate the complexity of subjective emotional experiences in everyday life. Of note, Asutay et al. (2021) found that the magnitude of the *peak* effect (rather than the *end*) increased with sequence length. While their study differed from ours in several other aspects, including stimulus modality (images *vs.* movies), emotional-sequence composition (pure *vs.* mixed emotions), and the duration of the individual stimuli (fixed *vs.* varied), results from this and other studies converge to indicate that temporally-extended experiences bias retrospective emotion towards 'shortcuts' of the past.

Although both peaks and ends are thought to reflect moments characterized by high saliency and survival relevance (Fredrickson, 2000), it is likely that distinct mechanisms underlie these biases. *Peak* biases may stem from arousal-based saliency effects known to robustly modulate attention and memory, which depend in part on function of the amygdala (Dolcos et al., 2020; Yiend et al., 2010; Bisby et al., 2016; Bisby & Burgess, 2017). *End* biases, in contrast, are reminiscent of recency effects in memory, which are supported by a broad network encompassing the prefrontal cortex and hippocampus (Howard et al., 2006; Howard & Kahana, 2002; Rajah & McIntosh, 2006). Therefore, future research aiming to uncover the origins of each of those retrospective biases—and their interactions with temporal processing—could manipulate factors known to differentially impact saliency and recency effects. For instance, while item saliency can be increased by manipulating arousal (Sutherland & Mather, 2012), recency effects can be reduced by introducing interference immediately after the initial emotional event encoding (Glanzer & Cunitz, 1966). Duration neglect, on the other hand, may reflect sustained alterations in temporal context processing and binding during emotionally salient situations, putatively due to amygdala *versus* hippocampal coding trade-offs that can occur in high-intensity emotional contexts, in alignment with extant findings on emotional-episodic memory interactions (Bisby et al., 2016; Bisby & Burgess, 2017; Wang et al., 2022).

Our results also suggest that inter-individual variation in the structure of temporal memory has implications for emotional functioning (Wang et al., 2022). The positive correlation between temporal duration errors and dispositional negativity identified in this study suggests that individuals at higher risk for mood and anxiety disorders may be prone to subjectively dilating the duration of negative (*vs.* positive) events in memory, consistent with recent computational models of the interactions between mood and contextual memory (Cohen & Kahana, 2022; Palombo & Cocquyt, 2020; Talmi et al., 2019; Wang et al., 2022). *Negativity bias*, the tendency to attend to and remember negative over positive information, is a hallmark of mood disorders (Norris, 2021). Our finding aligns with this extant body of work, and raises the possibility that individuals with trait negative disposition may remember negative events as longer-lasting; or conversely, that the trait-like propensity to dilate the duration of negative emotional experiences relative to positive experiences in memory—due to weaker temporal-context encoding and/or stronger emotion-driven distortions in temporal context—may increase susceptibility to mood disorders (Cohen & Kahana, 2022; Talmi et al., 2019). Moving forward, it will be important to uncover how the remembered duration of negative emotional events is dilated in individuals with higher dispositional NA, including disentangling whether these effects may be due to differential *encoding* of the temporal context surrounding negative events (Mogg et al., 1992), *vs.* whether positive and negative experiences are similarly encoded but differentially "compressed" during consolidation and/or accessible during retrieval (Bellmund et al., 2020; Cohen & Kahana, 2022; D'Argembeau et al., 2021; Talmi et al., 2019).

Contrary to our prediction, we did not find associations between temporal order memory and retrospective emotion biases or dispositional NA. These null results resonate with a growing literature underscoring dissociations between temporal duration and order memory in emotional contexts: While consistent emotion-driven distortions in duration memory have been noted (e.g., dilation of the remembered duration of negative events; Campbell & Bryant, 2007; Johnson & MacKay, 2019; Loftus et al., 1987; Stetson et al., 2007), mixed results have been reported for temporal memory—including evidence of both emotion-induced temporal memory impairment (Huntjens et al., 2015; Maddock & Frein, 2009) and enhancement (Dev et al., 2022; Riegel et al., 2023; Schmidt et al., 2011) (for reviews, see Palombo & Cocquyt, 2020; Petrucci & Palombo, 2021). This dissociation may stem in part from partially distinct memory-retrieval processes that have been implicated in temporal duration and order memory judgments—such as recollection and familiarity (Brunec et al., 2017). For instance, Brunec et al. (2017) found more accurate duration memory for neutral events when participants reported "reexperiencing" (i.e., recollecting) the events with rich details, compared with merely "knowing" (i.e., feeling familiar about) the events. In contrast, temporal order memory was not modulated by whether events were retrieved with a sense of recollection or familiarity. At the neural level, both temporal duration and order memory may rely on hippocampal-based processes that facilitate item-context and inter-item binding (Bellmund et al., 2020; Clewett & Davachi, 2019; Eichenbaum et al., 2007; Yonelinas et al., 2010), which can be hijacked by amygdala-driven emotional processing, resulting in temporal memory errors (Wang et al., 2022). In contrast, temporal order memory may additionally depend on item-strength signals in the perirhinal cortex (DuBrow & Dvachi, 2017; Jenkins & Ranganath, 2016), which are known to support familiarity-based memory processes (Eichenbaum et al., 2007; Yonelinas et al., 2010). Thus, amygdala-driven emotional processing can potentially impair both duration and order memory by interfering with hippocampal-based mnemonic processes that are pivotal for the retrieval of item-context and inter-item binding (Bisby et al., 2016; Bisby & Burgess, 2017; Wang et al., 2022)—while benefitting order memory via perirhinal-supported familiarity memory. This boost of temporal order memory following amygdala-dependent emotional processing may occur in at least two ways: through enhanced emotional item-strength signals (e.g., Murty et al., 2010; Ritchey et al., 2008, 2019) that can be used for temporal order inference (DuBrow & Dvachi, 2017; Howard et al., 2015) and/or by promoting familiarity-supported associative learning (Haskins et al., 2008; Petrucci & Palombo, 2021). Thus, it is possible that retrospective emotion biases are more robustly related to distortions in temporal duration memory, rather than in temporal order memory, which appears to rely on additional interactive mechanisms. Future work will be required to fully unveil the complex interplay between emotion and temporal memory, and to delineate the possible contributions of these distinct mnemonic processes to retrospective emotion biases and emotional functioning.

The following limitations of the current study warrant additional investigation. First, we calculated retrospective emotion biases as deviations from a putatively ideal, unbiased observer. Given limited information-processing capacity, whether the 'ideal observer' *should* be unbiased remains to be determined, as remembering all available details, without filtering, may not always be optimal (Vogel et al., 2005). Second, we measured temporal duration errors only at retrieval, which precluded elucidating whether temporal context distortions that may culminate in temporal memory errors already occurred during the initial encoding of emotional episodes. Future work may therefore consider the inclusion of online (behavioral and/or neural) metrics of temporal coding to uncover the time course of emotion-temporal coding interactions in emotional processing and memory. Third, the temporal order memory task preceded the administration of the duration memory task in our study. It is possible that performance in the duration memory task could have been higher had this task preceded the temporal order memory task, and/or had the order of these tasks been counterbalanced across participants. Fourth, the duration memory metric we employed indexed temporal dilation of negative experiences in memory *relative to* positive experiences. Therefore, disentangling whether temporal duration memory errors uncovered in our study resulted primarily from the dilation of negative experiences *vs.* compression of positive experiences requires future investigation.

Relatedly, our trait affect assessment centered on negative affect disposition. Given the import of positive hedonic processes for psychopathology (e.g., Heller et al., 2009), future research should incorporate scales that index hedonic and eudemonic positive affect to provide a more thorough examination of the associations between affective style, temporal memory, and retrospective emotion biases. Finally, the association between temporal duration errors and retrospective emotion identified in our study is correlational. Future work using behavioral (e.g., DuBrow & Davachi, 2014) or neural (e.g., Eichenbaum, 2014; Tambini et al., 2018; Wang et al., 2014) interventions to alter temporal memory will be required to determine their causal role in shaping retrospective emotion biases (Wang et al., 2022).

In closing, our findings suggest that ubiquitous retrospective emotion biases may arise from temporal memory capacity limits, and that high-fidelity temporal memory for the duration of emotional experiences is associated with a more adaptive affective style. Collectively, these findings underscore the fundamental interplay between emotion- and time-related mnemonic processes relevant for emotional functioning.

Transparency and Openness

Declaration of Conflicting Interests

The authors have no competing interests to declare.

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Open Science Practices

The present study was preregistered on OSF (https://osf.io/3h8ns), where we detailed how we determined the sample size, the study design and experimental manipulations, main and exploratory hypotheses, the data analysis plan, and all data exclusion criteria. Any discrepancies between the preregistered plan and the analyses in the manuscript were detailed in *Supplemental Material*. Other materials, including the data, scripts used for running the experiment, and data analysis scripts, can also be found here (https://osf.io/3h8ns).

Author's Contribution

Mengsi Li and Regina C. Lapate contributed equally to conceptualization, investigation, and methodology. Mengsi Li served as lead for data curation, formal analysis, project administration, validation, visualization, and writing–original draft. Regina C. Lapate served as lead for funding acquisition, resources, and supervision. Regina C. Lapate served in a supporting role for formal analysis and visualization. Mengsi Li and Regina C. Lapate contributed equally to writing–review and editing.

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Table 1. Overview of the analysis and fixed-effect estimates within the hierarchical mixed-effects regression models (m0-m3) testing duration neglect and the peak–end biases at the group level. The comparison between m1.1 (the average model) and m1.2 (the duration-weighted average model) suggests a significant role of duration of individual momentary ratings in predicting retrospective emotion ratings. Models m2-3 indicate a peak effect (driven by negative peak momentary ratings) and an end effect.

	m0		**m1.1**		**m1.2**		**m2**		**m3**	
Predictors	*β*	*p*	*β*	*p*	*β*	*p*	*β*	*p*	*β*	*p*
(Intercept)	4.57	**<0.001**	-0.50	**0.01**	0.24	0.14	0.08	0.56	-0.26	0.29
List	0.34	0.21	0.16	0.41	0.08	0.65	0.22	0.13	0.24	0.10
Average			1.04	**<0.001**						
Duration-weighted average					0.88	**<0.001**	0.59	**<0.001**	0.57	**<0.001**
End							0.31	**<0.001**	0.31	**<0.001**
Negative peak									0.14	**<0.001**
Positive peak									0.03	0.39
Marginal R^2	0.006		0.22		0.33		0.44		0.39	
Deviance	17253		16314		15860		15339		13386	
AIC	17263		16326		15872		15353		13404	
BIC	17295		16364		15910		15398		13460	
LL	-8627		-8157		-7930		-7670		-6693	

Note: AIC = Akaike information criterion. BIC = Bayesian information criterion. LL = log-Likelihood. Smaller AIC and BIC, and larger LL values indicate better model accuracy. Significant *p* values (< 0.05) are shown in bold. List is a control variable and m0 is the baseline model.