Arousal-Driven Serial Dependence: Internal States Modulate Perceived Duration

Si Cheng[1, 2, 3], Wenjie Jin[2], Xuanbing Shan[2], Elif Bengisu Kara[2], Sabiha Ecenur Bilgiç[2], Svetlana Salomasova[2], Quirin Unterguggenberger[2], Zhuanghua Shi[1, 2]

[1] General and Experimental Psychology, Department of Psychology, LMU Munich, Munich, Germany
[2] Chair of Neuro-cognitive psychology, Department of Psychology, LMU, Munich, Germany
[3] Department of Neurological Surgery, University of Texas Southwestern Medical Center, Dallas, TX, USA

Correspondence concerning this article should be addressed to Zhuanghua Shi: https://orcid.org/0000-0003-2388-6695, email: strongway@psy.lmu.de, telephone: +49(0)89/21805213, General and Experimental Psychology, Department of Psychology, LMU Munich, 80802 Munich, Germany.

Abstract

Emotional experience shapes not only how we perceive the present but also how the past influences our judgments. In this study, we examined how emotional arousal and valence modulate serial dependence in time perception—a phenomenon in which prior experiences bias current estimates. Using a duration reproduction task, participants viewed affective images drawn from the International Affective Picture System (IAPS) to induce high-arousal (positive or negative) or low-arousal (neutral) emotional states. We found that participants consistently overestimated durations in high-arousal conditions compared to those in low-arousal conditions, regardless of valence. Crucially, serial dependence effects were significantly amplified during high-arousal states. This effect was strongest when high-arousal trials were preceded by similar high-arousal trials, indicating a state-dependent intensification of sequential bias. Emotional valence, by contrast, had no significant effect on either temporal distortion or serial dependence. These findings suggest that emotional arousal, rather than valence, plays a key role in shaping the temporal integration of past and present, offering new insight into how affective states shape temporal cognition and serial dependence.

Keywords: Serial dependence; Time Perception; Arousal; Internal state

Introduction

Serial dependence - the tendency for recent experiences to systematically bias current perception and decisions - has been well-documented across various visual domains (Cicchini et al., 2014; Fischer & Whitney, 2014; Glasauer & Shi, 2022). Most studies have examined how features of the stimulus, such as uncertainty or contrast, influence this effect (Cicchini et al., 2023; Manassi et al., 2023; Ozkirli & Pascucci, 2023; Pascucci et al., 2023). Yet comparatively little work has explored how observers' internal state, particularly emotional state, modulates serial dependence.

Stimulus properties play a central role in shaping serial dependence (Ceylan & Pascucci, 2023; Cicchini et al., 2018; Manassi et al., 2018; Pascucci et al., 2019). The effect tends to grow stronger when the current stimulus is weak, uncertain, or briefly presented (Ceylan & Pascucci, 2023; Fritsche et al., 2017; Fritsche & de Lange, 2019). It is also enhanced when the previous stimulus was attended to and relevant to the task (Ceylan & Pascucci, 2023; S. Cheng, Chen, Yang, et al., 2024). Recent findings suggest that individual traits and cognitive states contribute as well. For example, confidence in prior judgments has been linked to greater sequential bias (Samaha et al., 2019), and individuals who strongly believe in temporal continuity exhibit more pronounced serial dependence (Glasauer & Shi, 2022). Together, these findings indicate that serial dependence reflects not just the external sensory environment but also internal states and expectation (Ozkirli & Pascucci, 2023). However, the role of emotion - a core driver of perception and cognition - remains underexplored.

Emotions shape how we perceive the world, not just in the moment, but across time. They influence a wide range of perceptual processes (Lapid et al., 2008; Penney et al., 2000; Shi et al., 2013; Treisman & Williams, 1984; Wittmann, 2009), and their effects often spill over, guiding cognition and behavior even in unrelated contexts (Gokce et al., 2021; Phelps et al., 2006; Schmidt & Schmidt, 2016). Among these effects, their influence on time perception is especially striking. As early as 1890, William James noted how emotions could distort time perception, stretching or compressing its felt passage time depending on the situation (James, 1890). Under stress, time may seem to slow; in joy, it often flies.

Emotional states are commonly described along two key dimensions: valence, which captures how pleasant or unpleasant a feeling is, and arousal, which reflects physiological activation (Bradley & Lang, 2017). Both dimensions have been shown to affect time perception. Positive and negative emotions alike tend to lengthen subjective durations compared to neutral ones (Bergmann et al., 2012; Costanzi et al., 2019; Cui et al., 2023; Droit-Volet & Gil, 2009; Grommet et al., 2019; Livesey et al., 2007). Arousal, in particular, has been identified as a central mechanism: high-arousal states lead to longer perceived durations, consistent with models suggesting that arousal speeds the internal clock, yielding more temporal "ticks" (Block et al., 2010; Droit-Volet & Gil, 2016; Matthews & Meck, 2016; Van Volkinburg & Balsam, 2014).

Critically, time perception is not fixed - it is pliable, warped not only by emotion but also by past experience. Two well-documented phenomena illustrate this: the central tendency effect, where long durations are underestimated and short durations are overestimated (Glasauer & Shi, 2021; Hollingworth, 1910; Jazayeri & Shadlen, 2010), and the sequential dependence effect, where current duration estimates are biased toward durations just experienced (Glasauer & Shi, 2022; Wehrman et al., 2023; Wiener et al., 2014). Unlike visual processing, time perception lacks dedicated sensory organs and relies more on internal cues - making it especially vulnerable to influences from attention, memory, and emotional state. Thus, working memory plays a key role in time perception. Recent evidence showed that when working memory load increases during the encoding of a duration, sequential dependence also increases (S. Cheng, Chen, & Shi, 2024). This suggests that working memory helps integrate current and prior information to guide time judgments and related decisions (Bae & Luck, 2020; Bliss et al., 2017; S. Cheng, Chen, Yang, et al., 2024; Kiyonaga et al., 2017). Since both arousal and memory are central to how time is perceived, it is likely that emotional states, through their effects on arousal and cognition, skew not only isolated time judgments but also the sequential biases that emerge across trials.

Despite robust evidence that both emotion and recent experience independently bias perception, we know surprisingly little about how emotional states might interact with recent experience to influence perception and decision-making. Emotions color our interpretations and leave their mark on memory, and alter how we make decisions (Forgas, 1995; Lerner & Keltner, 2000; Phelps et al., 2006, 2014). It is plausible that momentary shifts in emotional arousal recalibrate internal expectations or working memory processes, thereby influencing how prior stimuli affect current judgments. Yet, this possibility remains largely unexplored.

The present study addresses this gap by testing whether emotional arousal modulates temporal sequential dependence. Using a duration reproduction paradigm (S. Cheng et al., 2023a), we manipulated participants' emotional states through affective images drawn from the International Affective Picture System (IAPS; Lang et al., 2018). These images fell into three categories: positive high-arousal, negative high-arousal, and neutral low-arousal. Positive and negative images were presented in separate blocks, with high- and low-arousal images counterbalanced within each block to ensure that transitions between emotional states (e.g., from high to low arousal and vice versa) occurred with equal likelihood. During the task, participants viewed each image for a fixed duration, held that duration in memory, and then reproduced it. This design allowed us to examine how prior emotional arousal influenced current time judgments. We hypothesized that higher emotional arousal - whether positive or negative - would amplify serial dependence. Specifically, we predicted that high-arousal states, by increasing cognitive load or introducing sensory noise, would lead participants to lean more heavily on recent experiences to inform current judgments, thereby enhancing temporal sequential biases. Conversely, we expected that low-arousal states

would promote more accurate ecoding of current durations, reducing reliance on prior trials and weakening serial dependence.

Method

Participants

Twenty-one volunteers participated in this study (13 females, 8 males; age ranged from 19 to 26, mean ± SD: 23.00 ± 1.80 years). Prior research (Bae & Luck, 2020; S. Cheng et al., 2023a; Fischer et al., 2020; Fischer & Whitney, 2014) has shown large effect sizes for the serial dependence effect (Cohen's d > 0.70). With an effect size of 0.70, $\alpha = .05$, and a power of 80% (1-β), we calculated a priori power analysis and obtained a minimum of 19 participants according to G*Power 3.1 (Faul et al., 2007). On the safe side, we increased the sample size to 21. Participants signed the informed consent form before the experiment commenced and received compensation at a rate of 9 Euros/hour. The study was approved by the ethics committees of the Psychology Department at LMU Munich.

Stimuli and procedure

To evoke distinct emotional states, we curated 260 images from the International Affective Picture System (IAPS; Lang et al., 2018), selecting them based on ratings of arousal and valence. Our aim was clear: induce high-arousal emotional responses using positive and negative images, while maintaining a neutral, low-arousal baseline. Twenty images (10 neutral, 5 negative, and 5 positive) were used during practice, and the remaining 240 images were reserved for the main experiment. These were evenly distributed across three categories: 80 high-arousal negative images, 80 high-arousal positive images, and 80 low-arousal neutral images. The emotional properties of these images were confirmed through their normative ratings: positive images had a mean arousal score of 5.96 and a valence of 7.07; negative images scored higher in arousal (6.84) but low in valence (1.84); neutral images fell near the midpoint for both dimensions (arousal = 5.03; valence = 5.03). Statistical comparisons confirmed significant differences in both arousal and valence ratings between the negative, neutral, and positive image categories (all *p*s < .001).

To standardize visual input, we resized all images to subtend 10.85 × 8.06°) and adjusted their luminance to 58 cd/m^2. A custom mosaic image, matching the dimensions and average luminance of the affective images, was generated and used during reproduction to ensure consistency in the visual presentation. Stimulus presentation and data collection were controlled using PsychoPy3 (Peirce et al., 2019). Participants were seated in a soundproof, dimly lit room with their heads positioned on a chinrest 60 cm from a 21-inch CRT monitor (refresh rate: 85 Hz). All images were presented against a light grey background (luminance: 39.3 cd/m^2).

The present study employed a duration reproduction paradigm (S. Cheng et al., 2023b; Shi et al., 2022), illustrated in Figure 1. Each trial began with a fixation cross (visual angle: 0.5°) for 0.5 s. Then, a single image appeared at the center of the screen, marking the beginning of the duration encoding phase. It remained visible for one of five durations (0.8, 1.0, 1.2, 1.4, or 1.6 secs), randomly selected. Participants were instructed to memorize the duration of the image. Following a 0.5-sec blank screen, a central black dot cue (0.5°) signaled the reproduction phase. Participants were instructed to press and hold the down-arrow key to reproduce the previously seen duration. They were free to begin reproduction at their own pace, provided it was within a 10-second limit. Upon keypress, the mosaic image was displayed in place of the affective stimulus and remained on-screen until the key was released. The held duration was recorded as the reproduced interval.

To guide performance, participants received immediate visual feedback after each trial. One of five dark gray circles, arranged from left to right, appeared for 0.5 secs, corresponding to their relative reproduction accuracy: large underestimation (< -30%), moderate underestimation ([-30%, -5%]), near-perfect reproduction ([-5%, 5%]), moderate overestimation ([5%, 30%]), and large overestimation (> 30%).

Before the formal experiment, participants completed 20 practice trials to familiarize themselves with the task. The formal experiment consisted of 640 trials, divided into 16 blocks of 40 trials each. These were split across two sessions of eight blocks, separated by a 10-minute break.

To systematically manipulate emotional context, each session contained four positive-type blocks (high-arousal positive + neutral stimuli) and four negative-type blocks (high-arousal negative + neutral stimuli). Within each session, 80 high-arousal images (positive or negative) were randomly paired with 80 neutral images. Importantly, the same set of 80 neutral images appeared in both block types, but never repeated within the same block. To assess the influence of emotional arousal on serial dependence, we categorized trials based on the emotional arousal of the current and previous images. This resulted in four transition types: High → High (HH), High → Low (HL), Low → Low (LL), and Low → High (LH), analyzed separately for positive- and negative-type blocks. The trial sequence was carefully balanced to ensure equal representation of each transition type. Across all conditions, the five target durations were randomly distributed, ensuring that each appeared equally often.

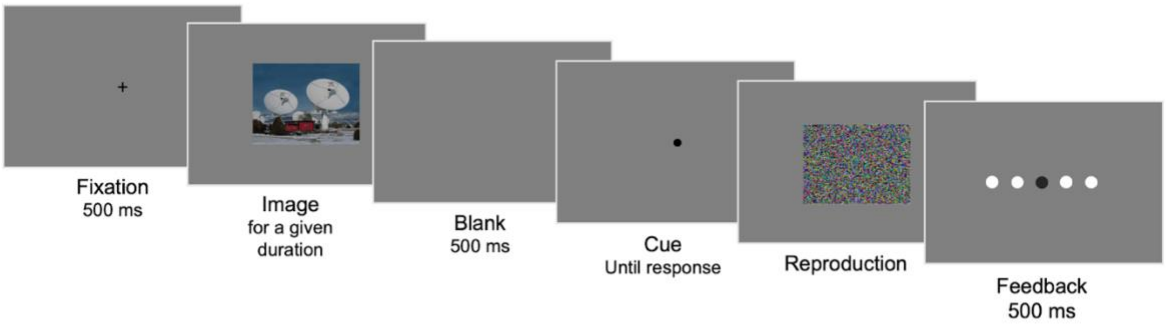

Figure 1. Schematic illustration of the experimental procedure. Each trial started with a fixation cross (500 ms), followed by an image (a neutral image with low arousal in the illustration) that appeared on the center of the screen for a given duration (randomly selected from 0.8, 1.0, 1.2, 1.4, and 1.6 s). Participants were asked to remember the duration. Then, a black dot prompted participants to reproduce the duration by pressing (a mosaic was triggered by the keypress) and holding the down arrow key on the keyboard as long as the perceived duration from the given image. After reproduction, participants receive visual feedback indicating their reproduction accuracy.

Data analysis

We computed reproduction error as the difference between the reproduced and actual durations on each trial. Reaction time (RT) was recorded from the onset of the reproduction cue (the black dot) to the initiation of the keypress. To ensure clean data, we excluded the first trial of each block - typically less stable due to initial adjustments and no prior stimulus - resulting in the removal of 16 trials. Additional outliers, defined as reproduction errors or RTs exceeding three standard deviations from the participant's mean, were discarded. These accounted for 2.11% of all trials (ranging from 5 to 22 trials per participant).

The remaining trials were grouped into four core conditions based on emotional block type (positive vs. negative) and arousal level (high vs. low). For each condition, we calculated the standard deviation (SD) of reproduction errors as a measure of variability in duration reproduction. We ran two-way repeated measurement ANOVAs on both RTs and SDs, with valence (positive vs. negative) and arousal (high vs. low) as within-subject factors.

Central tendency effect. To assess the central tendency bias—the tendency to overestimate short durations and underestimate long durations—we used a linear regression model relating the reproduction error (E_n) to the centered current duration ($Tc_n=T_n-1.2$):

$$En=aTc_n + b, \quad (1)$$

Here, the absolute slope $|a|$ reflects the strength of the central tendency effect: a slope of 0 indicates no bias, where a value between 0 to 1 represents a central tendency effect (with 1 indicating perfect bias). The intercept *b* captures general over- or underestimation.

Sequential dependence effect. To examine how past experiences influenced current estimates, we tested for sequential dependence by regressing current reproduction error (Errorn) on the duration of the previous trials (centered, $Tc_{n-1}=T_{n-1}-1.2$) (Holland & Lockhead, 1968; Jesteadt et al., 1977):

$$En= cTc_{n-1}+ d, \quad (2)$$

The slope *c* reflects the degree of sequential bias (e.g., Glasauer & Shi, 2022; Jesteadt et al., 1977), with positive slopes indicating assimilation (attraction toward the previous duration) and negative slopes indicating repulsion. The intercept *d* again represents general bias, similar to the *b* in Eq. (1).

To explore how serial dependence unfolds across time, we extended this analysis to examine how the current trial's reproduction error (En) was influenced by durations from not only the previous trial (T_{n-1}) but also from earlier trials (T_{n-2}, and T_{n-3}). Additionally, for a sanity check, we also analyzed sequential effects on future durations (T_{n+1} and T_{n+2}). The slope values from these regressions served as indices of serial dependence. To control for Type I error due to multiple comparisons, we applied the Bonferroni correction, adjusting the significance threshold to α/n, where α is the overall significance level (e.g., 0.05) and n is the number of comparisons conducted.

Results

The Central-tendency Effect

Figure. 2A plots reproduction errors against current durations, broken down by emotional arousal (high vs. low) within both positive and negative valence blocks. Across all conditions, participants showed a reliable central tendency bias - short durations were overestimated, long durations underestimated - with little difference between emotional contexts.

In positive valence blocks, central tendency indices (reflected as negative regression coefficients) averaged 0.469 ± 0.034 for high arousal stimuli and 0.448 ± 0.039 for low arousal stimuli. In negative valence blocks, indices were slightly higher: 0.494 ± 0.043 for high arousal stimuli and 0.467 ± 0.042 for low arousal stimuli (see Figure. 2B). All indices were significantly above zero (*t*s > 11.03, *p*s < .001), confirming the consistent central tendency effect across all conditions. A two-way repeated-measures (rm) ANOVA revealed no significant main effects of Valence and Arousal, nor any interaction between them (all *F*s < 1.607, *p*s > .219, p2 < .004). This consistency likely stems from the use of the same duration range in all conditions, which may have fostered a stable prior representation of time. This pattern echoes previous findings suggesting that consistent stimulus distributions encourage generalized temporal priors (Roach et al., 2017).

We then assessed the general bias (*b*), which captures overall bias in duration reproduction. In positive valence blocks, participants underestimate duration by 14 ± 15 ms in the high-arousal condition and 35 ± 16 ms in the low-arousal condition. In negative valence blocks, underestimations were 18 ± 16 ms and 34 ± 13 ms, respectively (see Figure 2C). Here, the pattern shifted. A two-way rmANOVA on intercept values (*b*) revealed a significant main effect of Stimulus Arousal ($F_{(1,20)}$ = 13.56, p = .001, p2 = 0.018). Regardless of valence, high arousal led to less underestimation, suggesting a tendency to perceive durations as longer. Neither the effect of Valence ($F_{(1,20)}$ = 0.063, p = .804) nor the interaction ($F_{(1,20)}$ = 0.501, p = .487) reached significance.

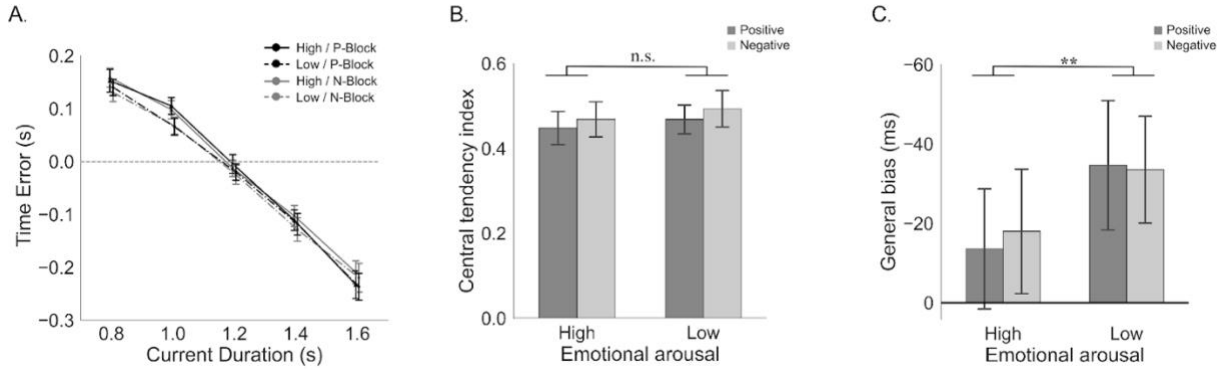

Figure 2. (**A**) Reproduced duration. The mean reproduction error was plotted separately for emotional valence (positive or negative) and emotional arousal (high or low). (P-Block: Positive block type; N-Block: Negative block type.) (**B**) Central tendency effect. The mean central tendency indices (the absolute slope |*a*| in Eq. (1)) are plotted separately for emotional valence (positive or negative) and emotional arousal (high or low). (**C**). General biases (intercept *b* in Eq. (1)) are plotted separately for emotional valence (positive or negative) and emotional arousal (high or low). Error bars represent ± SEM. ***p* < .01.

The Serial-dependence Effect

As shown in Figure 3A, reproduction errors systematically increased with the duration of the previous trial, reflecting a clear serial dependence effect across all conditions. In both positive and negative valence blocks, regression slopes were significantly greater than 0 (ts > 2.787, ps < 0.011), confirming robust assimilation toward prior durations.

While a three-way ANOVA on slope values revealed no significant interaction involving valence, current arousal, and previous arousal ($F_{(1,160)} = 0.292$, $p = .590$), a clearer pattern emerged when we zoomed in on arousal effects. There was no main effect of Valence ($F_{(1,160)} = 0.030$, $p = .863$), and no effect of Previous Arousal ($F_{(1,160)} = 0.007$, $p = .936$), but a significant main effect of Current Arousal ($F_{(1,160)} = 6.296$, $p = .013$, p2 = 0.038). Participants showed stronger serial dependence when the current stimulus was high in arousal.

More intriguingly, a Current × Previous Arousal interaction emerged ($F_{(1,160)} = 4.527$, $p = .035$, p2 = 0.028), suggesting that serial dependence is not simply a carryover from the past - it intensifies when both current and prior stimuli are emotionally arousing. Post-hoc comparisons confirmed this: when both current and previous trials were high-arousal, serial bias peaked ($t_{(20)} = 2.450$, $p = .047$, $BF_{10} = 2.485$, Bonferroni correction).

These findings highlight the role of emotional arousal - but not valence - in shaping how the recent past pulls on the present. Figure 3C further illustrates the pattern of general bias across arousal conditions, which was similar to Figure 2C.

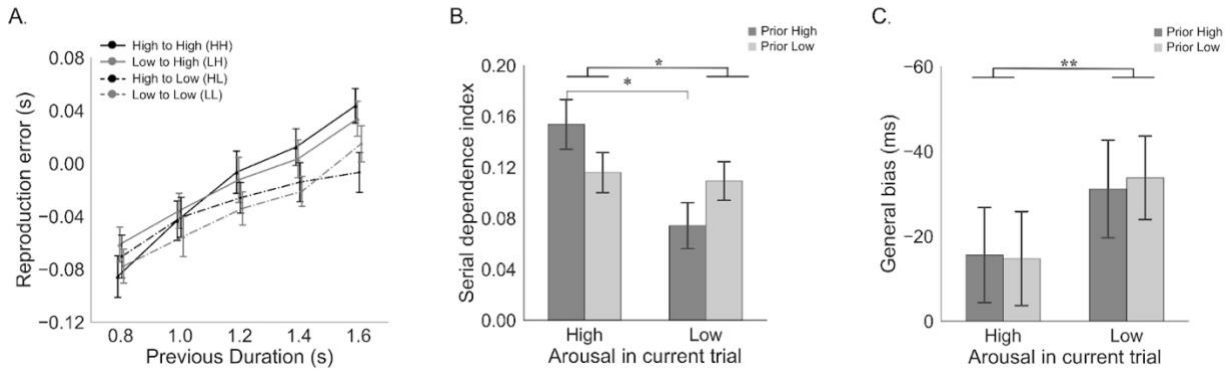

Figure 3. Serial dependence effect. (**A**). Mean reproduction errors are plotted as a function of previous durations for the high arousal to high arousal (HH), low arousal to high arousal (LH), high arousal to low arousal (HL), and low arousal to low arousal (LL) conditions. (**B**). The serial dependence indices (the slope c in Eq. (2)) are shown separately for current high and low arousal conditions, with comparisons based on whether the previous trial's arousal was high or low. (**C**). General biases (intercept d in Eq. (2)) are shown separately for current high and low arousal conditions, with comparisons based on whether the previous trial's arousal was high or low. Error bars represent ± SEM. **$p < .01$, *$p < .05$.

To explore how far back these sequential effects extended, we correlated current reproduction errors with durations from trials n-1, n-2, and n-3, and for verification, with future trials (n+1 and n+2) as well (see Figure 4). In current high-arousal conditions, the serial dependence extended beyond the immediately prior trial: when the prior two trials (n-2) were also high in arousal, a significant influence was still detectable (slope: 0.062 ± 0.017, $t_{(20)} = 3.723$, $p = .007$, Bonferroni-corrected). This extended effect did not appear in low-arousal contexts, suggesting a specific amplifying role for sustained emotional intensity. Importantly, no evidence of bias from future trials emerged (*ps* > .067), ruling out confounds related to temporal autocorrelation or task structure (Cicchini et al., 2014).

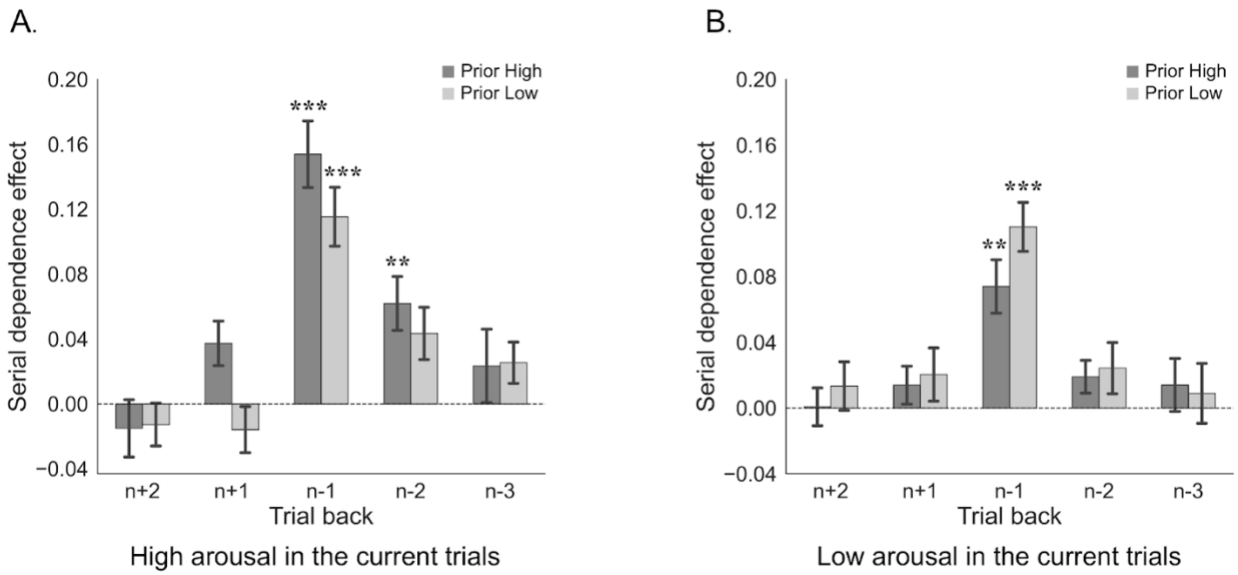

Figure 4. Serial dependence effect in the preceding trials (n-1, n-2, and n-3) and in the future trials (n+1, n+2). (**A**). Serial dependence indices for the current high arousal trials, plotted separately for the prior high arousal and low arousal conditions. (**B**). Serial dependence indices for the current low arousal trials, plotted separately for the prior high arousal and low arousal conditions. Error bars represent ± SEM. ***$p < .001$, **$p < .01$, *$p < .05$.

Despite these shifts in sequential bias, the precision of time estimation remained unaffected. Standard deviations of reproductions were nearly identical across conditions. A two-way rmANOVA confirmed no effects of Arousal, Valence, or their interaction on variability (*F*s < 1.77, *p*s >.199). However, reaction times (RTs) told a different story. Participants were slower to initiate reproduction following high-arousal stimuli (0.641 ± 0.051 s for the positive block and 0.633 ± 0.052 s for the negative blocks) than

low-arousal stimuli (0.617 ± 0.049 s and 0.612 ± 0.043 s for the positive and negative blocks, respectively). A two-way rmANOVA on RTs showed a significant main effect of Emotional Arousal, $F_{(1,20)} = 7.035$, $p = .015$, p2 = 0.260, confirming that high arousal delayed response initiation - possibly due to increased cognitive load or attentional capture. No effects of Valence or interaction were observed (*Fs* < 0.322, *ps* > .577).

Discussion

This study investigated how emotional states influence serial dependence in time perception. By presenting participants with emotionally evocative images from the International Affective Picture System (IAPS), we induced high-arousal (positive and negative) and low-arousal (neutral) states and asked participants to reproduce image durations. The results were clear: participants tended to overestimate durations when emotionally aroused, and crucially, serial dependence - the pull of the past on present judgments - grew stronger under high arousal, especially when both the current and preceding trials involved high-arousal stimuli. In contrast, emotional valence - whether the emotion was positive or negative - had no measurable effect on either duration reproduction or serial bias. Together, these findings highlight emotional arousal, not valence, as a key modulator of how we experience and reproduce time.

Our findings echo and extend a well-established body of work linking arousal to overestimation of time. Internal clock models have long proposed that arousal accelerates an internal pacemaker, resulting in the accumulation of more temporal "pulses" for the same objective duration (Block et al., 2010; Droit-Volet, 2013; Droit-Volet & Gil, 2009; Droit-Volet & Meck, 2007; Gibbon et al., 1984; Grommet et al., 2019). When these pulse counts are compared against a stored memory of time, the inflated count leads to the sensation that more time has passed. This framework is supported by a range of behavioral and neurochemical studies: dopaminergic modulation in both animals and humans shifts pacemaker speed (R.-K. Cheng et al., 2006; Mella et al., 2011; van der Veen et al., 2017; Yin et al., 2022), while changes in body temperature produce parallel effects on perceived time (Wearden & Penton-Voak, 1995). Our data are consistent with this model - showing a reliable overestimation of durations in high-arousal states.

What's new here is the link between arousal and serial dependence. While most research on serial dependence has centered on stimulus feature - like uncertainty, contrast, or attention (Cicchini et al., 2023; Manassi et al., 2023; Ozkirli & Pascucci, 2023; Pascucci et al., 2023) - we show that an observer's internal state, specifically their arousal level, also modulates the strength of this temporal bias. Serial dependence was strongest when the current stimulus was emotionally intense, and even more so when that intensity had carried over from the previous trial. Remarkably, the bias extended to trials two steps back - but only under sustained high-arousal conditions.

What might arousal intensify serial dependence? One explanation lies in the shifting dynamics of attention. High arousal states are known to narrow attentional focus (P. A. Gable & Harmon-Jones, 2008; P. Gable & Harmon-Jones, 2010; Harmon-Jones et al., 2010), a phenomenon often accompanied by increased cognitive load or delayed reorientation to the task (Easterbrook, 1959; Fredrickson & Branigan, 2005; Lam et al., 2020). This aligns with our observed slower reaction times for high-arousal stimuli: participants may have been momentarily absorbed by the emotional content, delaying their re-engagement with the timing task. As a result, their encoding of the current duration may have weakened, leaving them more reliant on recent memory traces to guide their reproduction - a hallmark of stronger serial dependence. This attentional interpretation fits neatly with broader theories of affect and cognition. Emotional arousal not only colors how we perceive individual moments - it shapes the continuity between them, subtly altering the balance between present perception and past experience. In this perspective, our results suggest that when attention is compromised by emotional intensity, the brain may compensate by drawing more heavily on recent history to stabilize judgments.

A second explanatory account builds on the idea that serial dependence serves an adaptive function, helping the perceptual system stabilize judgments in the face of noise and uncertainty. Rather than being a flaw, this bias toward recent experience may be a strategic mechanism - a way for the brain to smooth over the instability of the volatile world (Cicchini et al., 2017, 2018; Fischer & Whitney, 2014). Moment-to-moment changes in emotional arousal, then, could act as an internal source of noise, subtly catering how the brain weighs past and present inputs. This interpretation is consistent with work showing that external uncertainty - for instance, reductions in contrast, spatial frequency, and cardinality - increases reliance on prior stimuli (Ceylan et al., 2021; Cicchini et al., 2017, 2018; Manassi et al., 2018). Under such noisy conditions, recent perceptual history becomes more informative than current, unreliable inputs. Our findings extend this framework: emotional arousal may generate a similar kind of perceptual uncertainty, prompting the system to lean more heavily on the recent past. Indeed, participants in high-arousal states were more likely to rely on the durations of preceding trials - suggesting that arousal not only distorts the perception of individual durations but modulates the weight of temporal memory. Remarkably, this influence extended up to two trials back, reinforcing the idea that arousal acts as a multiplier of sequential effects, even when the stimulus itself remains unchanged.

These two accounts - attentional disruption and adaptive integration under uncertainty - need not be mutually exclusive. On the contrary, they likely reflect interacting processes: emotional arousal may impair attention to the present while simultaneously increasing the perceptual system's need to rely on recent inputs.

What's particularly striking is that serial dependence peaked when both the current and prior emotional states were high in arousal. This pattern runs counter to the traditional Bayesian framework,

which suggests that when past information is noisy or unreliable, the system should prioritize current inputs (de Lange et al., 2018; Kersten et al., 2004; Knill & Pouget, 2004). Instead, we observed the opposite: the influence of the past intensified, even though high arousal could reasonably degrade the precision of both current and previous percepts. This finding invites a 'state-dependent' account of serial dependence, in which the influence of prior stimuli is not fixed, but dynamically modulated by internal states - such as arousal. From this perspective, perceptual decisions emerge not only from computations over stimulus properties or learned priors but also from shifting internal modes of processing. In high-arousal states, where perceptual systems may be taxed or overactivated, recent experiences gain salience and are granted more authority in guiding the present. Support for this view comes from studies manipulating stimulus noise: when both current and previous trials were degraded (e.g., high to high noise), serial dependence increased compared to transitions from low to high noise (Gallagher & Benton, 2022; Lidström, 2023). Similarly, with degraded face stimuli, serial dependence was stronger when perceptual quality remained consistently poor across trials (Liberman et al., 2018). These patterns point toward a broader principle: continuity in internal state - whether driven by arousal, noise, uncertainty, or expectation - amplifies reliance on the past (Glasauer & Shi, 2022).

Our study did not find evidence that emotional valence moderates either temporal distortion or serial dependence. This aligns with mixed findings in the literature: While some studies report that both positive and negative stimuli lead to temporal overestimation compared to neutral stimuli (Jones et al., 2017; Li & Tian, 2020), others suggest that negative stimuli produce stronger distortions (Buetti & Lleras, 2012; Mereu & Lleras, 2013). A likely explanation for these discrepancies lies in the relative roles of valence versus arousal. Many valence-related timing effects only emerge under high-arousal conditions (Droit-Volet et al., 2004), and in our study, both positive and negative images elicited equally high arousal. This likely masked any valence-specific effects, as the influence of arousal overrode potential differences in emotional tone. In short, where arousal is held constant, valence may not exert a detectable influence on perceived duration or sequential processing.

Together, our results reveal that serial dependence in time perception is not merely a product of stimulus dynamics or sensory uncertainty, but it is also profoundly shaped by the observer's internal emotional state. We found that high arousal - regardless of whether it was positive or negative - both distorted the perception of time and amplified the impact of prior experience on current judgments. Most strikingly, the strongest serial biases arose when high-arousal trials followed other high-arousal trials, suggesting a form of perceptual inertia tied to sustained emotional intensity. These findings support a state-dependent view of perception, in which temporal decisions are not isolated computations but evolve from the ongoing interplay between memory, emotion, and expectation. Our findings also offer new insight into

how arousal not only warps our experience of individual moments but also shapes the structure of temporal continuity, influencing how we integrate the past into the present.

Declaration of competing interest

The authors declare no competing interests.

Data and code availability statement

The data and analysis code that support the findings of this study will be made available from the author, Si Cheng (chengsi123456@gmail.com), upon reasonable request.

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References

Bae, G.-Y., & Luck, S. J. (2020). Serial dependence in vision: Merely encoding the previous-trial target is not enough. *Psychonomic Bulletin & Review*, *27*(2), 293–300. https://doi.org/10.3758/s13423-019-01678-7

Bergmann, H. C., Rijpkema, M., Fernández, G., & Kessels, R. P. C. (2012). The effects of valence and arousal on associative working memory and long-term memory. *PloS One*, *7*(12), e52616. https://doi.org/10.1371/journal.pone.0052616

Bliss, D. P., Sun, J. J., & D'Esposito, M. (2017). Serial dependence is absent at the time of perception but increases in visual working memory. *Scientific Reports*, *7*(1), 1–13. https://doi.org/10.1038/s41598-017-15199-7

Block, R. A., Hancock, P. A., & Zakay, D. (2010). How cognitive load affects duration judgments: A meta-analytic review. *Acta Psychologica*, *134*(3), 330–343. https://doi.org/10.1016/j.actpsy.2010.03.006

Bradley, M. M., & Lang, P. J. (2017). International Affective Picture System. In V. Zeigler-Hill & T. K. Shackelford (Eds.), *Encyclopedia of Personality and Individual Differences* (pp. 1–4). Springer International Publishing. https://doi.org/10.1007/978-3-319-28099-8_42-1

Buetti, S., & Lleras, A. (2012). Perceiving control over aversive and fearful events can alter how we experience those events: an investigation of time perception in spider-fearful individuals. *Frontiers in Psychology*, *3*, 337. https://doi.org/10.3389/fpsyg.2012.00337

Ceylan, G., Herzog, M. H., & Pascucci, D. (2021). Serial dependence does not originate from low-level visual processing. *Cognition*, *212*, 104709. https://doi.org/10.1016/j.cognition.2021.104709

Ceylan, G., & Pascucci, D. (2023). Attractive and repulsive serial dependence: The role of task relevance, the passage of time, and the number of stimuli. *Journal of Vision*, *23*(6), 8. https://doi.org/10.1167/jov.23.6.8

Cheng, R.-K., MacDonald, C. J., & Meck, W. H. (2006). Differential effects of cocaine and ketamine on time estimation: implications for neurobiological models of interval timing. *Pharmacology, Biochemistry, and Behavior*, *85*(1), 114–122. https://doi.org/10.1016/j.pbb.2006.07.019

Cheng, S., Chen, S., Glasauer, S., Keeser, D., & Shi, Z. (2023a). Neural mechanisms of sequential dependence in time perception: the impact of prior task and memory processing. *Cerebral Cortex* . https://doi.org/10.1093/cercor/bhad453

Cheng, S., Chen, S., Glasauer, S., Keeser, D., & Shi, Z. (2023b). Neural mechanisms of sequential dependence in time perception: the impact of prior task and memory processing. *Cerebral Cortex* . https://doi.org/10.1093/cercor/bhad453

Cheng, S., Chen, S., & Shi, Z. (2024). Opposing sequential biases in direction and time reproduction: Influences of task relevance and working memory. *British Journal of Psychology* . https://doi.org/10.1111/bjop.12728

Cheng, S., Chen, S., Yang, X., & Shi, Z. (2024). The impact of task measurements on sequential dependence: a comparison between temporal reproduction and discrimination tasks. *Psychological Research*, 1–14. https://doi.org/10.1007/s00426-024-02023-x

Cicchini, G. M., Anobile, G., & Burr, D. C. (2014). Compressive mapping of number to space reflects dynamic encoding mechanisms, not static logarithmic transform. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(21), 7867–7872. https://doi.org/10.1073/pnas.1402785111

Cicchini, G. M., Mikellidou, K., & Burr, D. (2017). Serial dependencies act directly on perception. *Journal of Vision*, *17*(14), 6. https://doi.org/10.1167/17.14.6

Cicchini, G. M., Mikellidou, K., & Burr, D. C. (2018). The functional role of serial dependence. *Proceedings. Biological Sciences / The Royal Society*, *285*(1890). https://doi.org/10.1098/rspb.2018.1722

Cicchini, G. M., Mikellidou, K., & Burr, D. C. (2023). Serial Dependence in Perception. *Annual Review of Psychology*. https://doi.org/10.1146/annurev-psych-021523-104939

Costanzi, M., Cianfanelli, B., Saraulli, D., Lasaponara, S., Doricchi, F., Cestari, V., & Rossi-Arnaud, C. (2019). The Effect of Emotional Valence and Arousal on Visuo-Spatial Working Memory: Incidental Emotional Learning and Memory for Object-Location. *Frontiers in Psychology*, *10*, 2587. https://doi.org/10.3389/fpsyg.2019.02587

Cui, X., Tian, Y., Zhang, L., Chen, Y., Bai, Y., Li, D., Liu, J., Gable, P., & Yin, H. (2023). The role of valence, arousal, stimulus type, and temporal paradigm in the effect of emotion on time perception: A meta-analysis. *Psychonomic Bulletin & Review*, *30*(1), 1–21. https://doi.org/10.3758/s13423-022-02148-3

de Lange, F. P., Heilbron, M., & Kok, P. (2018). How Do Expectations Shape Perception? *Trends in Cognitive Sciences*, *22*(9), 764–779. https://doi.org/10.1016/j.tics.2018.06.002

Droit-Volet, S. (2013). Time perception, emotions and mood disorders. *Journal of Physiology, Paris*, *107*(4), 255–264. https://doi.org/10.1016/j.jphysparis.2013.03.005

Droit-Volet, S., Brunot, S., & Niedenthal, P. (2004). BRIEF REPORT Perception of the duration of emotional events. *Cognition & Emotion*, *18*(6), 849–858. https://doi.org/10.1080/02699930341000194

Droit-Volet, S., & Gil, S. (2009). The time-emotion paradox. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *364*(1525), 1943–1953. https://doi.org/10.1098/rstb.2009.0013

Droit-Volet, S., & Gil, S. (2016). The emotional body and time perception. *Cognition & Emotion*, *30*(4), 687–699. https://doi.org/10.1080/02699931.2015.1023180

Droit-Volet, S., & Meck, W. H. (2007). How emotions colour our perception of time. *Trends in Cognitive Sciences*, *11*(12), 504–513. https://doi.org/10.1016/j.tics.2007.09.008

Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behavior. *Psychological Review*, *66*(3), 183–201. https://doi.org/10.1037/h0047707

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/bf03193146

Fischer, Czoschke, S., Peters, B., Rahm, B., Kaiser, J., & Bledowski, C. (2020). Context information supports serial dependence of multiple visual objects across memory episodes. *Nature Communications*, *11*(1), 1932. https://doi.org/10.1038/s41467-020-15874-w

Fischer, & Whitney, D. (2014). Serial dependence in visual perception. *Nature Neuroscience*, *17*(5), 738–743. https://doi.org/10.1038/nn.3689

Forgas, J. P. (1995). Mood and judgment: the affect infusion model (AIM). *Psychological Bulletin*, *117*(1), 39–66. https://doi.org/10.1037/0033-2909.117.1.39

Fredrickson, B. L., & Branigan, C. (2005). Positive emotions broaden the scope of attention and thought-action repertoires. *Cognition & Emotion*, *19*(3), 313–332. https://doi.org/10.1080/02699930441000238

Fritsche, M., & de Lange, F. P. (2019). The role of feature-based attention in visual serial dependence. *Journal of Vision*, *19*(13), 21. https://doi.org/10.1167/19.13.21

Fritsche, M., Mostert, P., & de Lange, F. P. (2017). Opposite Effects of Recent History on Perception and Decision. *Current Biology: CB*, *27*(4), 590–595. https://doi.org/10.1016/j.cub.2017.01.006

Gable, P. A., & Harmon-Jones, E. (2008). Approach-motivated positive affect reduces breadth of attention. *Psychological Science*, *19*(5), 476–482. https://doi.org/10.1111/j.1467-9280.2008.02112.x

Gable, P., & Harmon-Jones, E. (2010). The motivational dimensional model of affect: Implications for breadth of attention, memory, and cognitive categorisation. *Cognition & Emotion*, *24*(2), 322–337. https://doi.org/10.1080/02699930903378305

Gallagher, G. K., & Benton, C. P. (2022). Stimulus uncertainty predicts serial dependence in orientation judgements. *Journal of Vision*, *22*(1), 6. https://doi.org/10.1167/jov.22.1.6

Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar Timing in Memory. *Annals of the New York Academy of Sciences*, *423*(1), 52–77. https://doi.org/10.1111/j.1749-6632.1984.tb23417.x

Glasauer, S., & Shi, Z. (2021). The origin of Vierordt's law: The experimental protocol matters. *PsyCh Journal*, *10*(5), 732–741. https://doi.org/10.1002/pchj.464

Glasauer, S., & Shi, Z. (2022). Individual beliefs about temporal continuity explain variation of perceptual biases. *Scientific Reports*, *12*(1), 10746. https://doi.org/10.1038/s41598-022-14939-8

Gokce, A., Zinchenko, A., Annac, E., Conci, M., & Geyer, T. (2021). Affective Modulation of Working Memory Maintenance: The Role of Positive and Negative Emotions. *Advances in Cognitive Psychology / University of Finance and Management in Warsaw*, *17*(2), 107–116. https://doi.org/10.5709/acp-0321-7

Grommet, E. K., Hemmes, N. S., & Brown, B. L. (2019). The Role of Clock and Memory Processes in the Timing of Fear Cues by Humans in the Temporal Bisection Task. *Behavioural Processes*, *164*, 217–229. https://doi.org/10.1016/j.beproc.2019.05.016

Harmon-Jones, E., Gable, P. A., & Peterson, C. K. (2010). The role of asymmetric frontal cortical activity in emotion-related phenomena: a review and update. *Biological Psychology*, *84*(3), 451–462. https://doi.org/10.1016/j.biopsycho.2009.08.010

Holland, M. K., & Lockhead, G. R. (1968). Sequential effects in absolute judgments of loudness. *Perception & Psychophysics*, *3*(6), 409–414. https://doi.org/10.3758/BF03205747

Hollingworth, H. L. (1910). The Central Tendency of Judgment. *The Journal of Philosophy, Psychology and Scientific Methods*, *7*(17), 461–469. https://doi.org/10.2307/2012819

James, W. (1890). *The principles of psychology, Vol I*. Henry Holt and Co. https://doi.org/10.1037/10538-000

Jazayeri, M., & Shadlen, M. N. (2010). Temporal context calibrates interval timing. *Nature Neuroscience*, *13*(8), 1020–1026. https://doi.org/10.1038/nn.2590

Jesteadt, W., Luce, R. D., & Green, D. M. (1977). Sequential effects in judgments of loudness. *Journal of Experimental Psychology. Human Perception and Performance*, *3*(1), 92–104. https://doi.org/10.1037//0096-1523.3.1.92

Jones, C. R. G., Lambrechts, A., & Gaigg, S. B. (2017). Using time perception to explore implicit sensitivity to emotional stimuli in autism spectrum disorder. *Journal of Autism and Developmental Disorders*, *47*(7), 2054–2066. https://doi.org/10.1007/s10803-017-3120-6

Kersten, D., Mamassian, P., & Yuille, A. (2004). Object perception as Bayesian inference. *Annual Review of Psychology*, *55*(1), 271–304. https://doi.org/10.1146/annurev.psych.55.090902.142005

Kiyonaga, A., Scimeca, J. M., Bliss, D. P., & Whitney, D. (2017). Serial Dependence across Perception, Attention, and Memory. *Trends in Cognitive Sciences*, *21*(7), 493–497. https://doi.org/10.1016/j.tics.2017.04.011

Knill, D. C., & Pouget, A. (2004). The Bayesian brain: the role of uncertainty in neural coding and computation. *Trends in Neurosciences*, *27*(12), 712–719. https://doi.org/10.1016/j.tins.2004.10.007

Lam, C. L. M., Leung, C. J., Yiend, J., & Lee, T. M. C. (2020). The implication of cognitive processes in emotional bias. *Neuroscience and Biobehavioral Reviews*, *114*, 156–157. https://doi.org/10.1016/j.neubiorev.2020.04.022

Lapid, E., Ulrich, R., & Rammsayer, T. (2008). On estimating the difference limen in duration discrimination tasks: a comparison of the 2AFC and the reminder task. *Perception & Psychophysics*, *70*(2), 291–305. https://doi.org/10.3758/pp.70.2.291

Lerner, J. S., & Keltner, D. (2000). Beyond valence: Toward a model of emotion-specific influences on judgement and choice. *Cognition and Emotion*, *14*(4), 473–493. https://doi.org/10.1080/026999300402763

Liberman, A., Manassi, M., & Whitney, D. (2018). Serial dependence promotes the stability of perceived emotional expression depending on face similarity. *Attention, Perception & Psychophysics*, *80*(6), 1461–1473. https://doi.org/10.3758/s13414-018-1533-8

Lidström, A. (2023). Serial dependence in facial identity perception and visual working memory. *Attention, Perception & Psychophysics*, *85*(7), 2226–2241. https://doi.org/10.3758/s13414-023-02799-x

Li, L., & Tian, Y. (2020). Aesthetic preference and time: Preferred painting dilates time perception. *SAGE Open*, *10*(3), 215824402093990. https://doi.org/10.1177/2158244020939905

Livesey, A. C., Wall, M. B., & Smith, A. T. (2007). Time perception: manipulation of task difficulty dissociates clock functions from other cognitive demands. *Neuropsychologia*, *45*(2), 321–331. https://doi.org/10.1016/j.neuropsychologia.2006.06.033

Manassi, M., Liberman, A., Kosovicheva, A., Zhang, K., & Whitney, D. (2018). Serial dependence in position occurs at the time of perception. *Psychonomic Bulletin & Review*, *25*(6), 2245–2253. https://doi.org/10.3758/s13423-018-1454-5

Manassi, M., Murai, Y., & Whitney, D. (2023). Serial dependence in visual perception: A meta-analysis and review. *Journal of Vision*, *23*(8), 18. https://doi.org/10.1167/jov.23.8.18

Matthews, W. J., & Meck, W. H. (2016). Temporal cognition: Connecting subjective time to perception, attention, and memory. *Psychological Bulletin*, *142*(8), 865–907. https://doi.org/10.1037/bul0000045

Mella, N., Conty, L., & Pouthas, V. (2011). The role of physiological arousal in time perception: psychophysiological evidence from an emotion regulation paradigm. *Brain and Cognition*, *75*(2), 182–187. https://doi.org/10.1016/j.bandc.2010.11.012

Mereu, S., & Lleras, A. (2013). Feelings of control restore distorted time perception of emotionally charged events. *Consciousness and Cognition*, *22*(1), 306–314. https://doi.org/10.1016/j.concog.2012.08.004

Ozkirli, A., & Pascucci, D. (2023). It's not the spoon that bends: Internal states of the observer determine serial dependence. In *bioRxiv* (p. 2023.10.19.563128). https://doi.org/10.1101/2023.10.19.563128

Pascucci, D., Mancuso, G., Santandrea, E., Della Libera, C., Plomp, G., & Chelazzi, L. (2019). Laws of concatenated perception: Vision goes for novelty, decisions for perseverance. *PLoS Biology*, *17*(3), e3000144. https://doi.org/10.1371/journal.pbio.3000144

Pascucci, D., Tanrikulu, Ö. D., Ozkirli, A., Houborg, C., Ceylan, G., Zerr, P., Rafiei, M., & Kristjánsson, Á. (2023). Serial dependence in visual perception: A review. *Journal of Vision*, *23*(1), 9. https://doi.org/10.1167/jov.23.1.9

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Penney, T. B., Gibbon, J., & Meck, W. H. (2000). Differential Effects of Auditory and Visual Signals on Clock Speed and Temporal Memory. *Journal of Experimental Psychology. Human Perception and Performance*, *26*(6), 1770–1787. https://doi.org/10.1037/0096-1523.26.6.1770

Phelps, E. A., Lempert, K. M., & Sokol-Hessner, P. (2014). Emotion and decision making: multiple modulatory neural circuits. *Annual Review of Neuroscience*, *37*, 263–287. https://doi.org/10.1146/annurev-neuro-071013-014119

Phelps, E. A., Ling, S., & Carrasco, M. (2006). Emotion facilitates perception and potentiates the perceptual benefits of attention. *Psychological Science*, *17*(4), 292–299. https://doi.org/10.1111/j.1467-9280.2006.01701.x

Roach, N. W., McGraw, P. V., Whitaker, D. J., & Heron, J. (2017). Generalization of prior information for rapid Bayesian time estimation. *Proceedings of the National Academy of Sciences*, *114*(2), 412–417. https://doi.org/10.1073/pnas.1610706114

Samaha, J., Switzky, M., & Postle, B. R. (2019). Confidence boosts serial dependence in orientation estimation. *Journal of Vision*, *19*(4), 25. https://osf.io/6uczk/. https://doi.org/10.1167/19.4.25

Schmidt, S. R., & Schmidt, C. R. (2016). The emotional carryover effect in memory for words. *Memory* , *24*(7), 916–938. https://doi.org/10.1080/09658211.2015.1059859

Shi, Z., Church, R. M., & Meck, W. H. (2013). Bayesian optimization of time perception. *Trends in Cognitive Sciences*, *17*(11), 556–564. https://doi.org/10.1016/j.tics.2013.09.009

Shi, Z., Theisinger, L. A., Allenmark, F., Pistorius, R. L., Müller, H. J., & Falter-Wagner, C. M. (2022). Predictive coding in ASD: inflexible weighting of prediction errors when switching from stable to volatile environments. In *bioRxiv* (p. 2022.01.21.477218). https://doi.org/10.1101/2022.01.21.477218

Treisman, M., & Williams, T. C. (1984). A theory of criterion setting with an application to sequential dependencies. *Psychological Review*, *91*(1), 68–111. https://doi.org/10.1037/0033-295X.91.1.68

van der Veen, D. R., Riede, S. J., Heideman, P. D., Hau, M., van der Vinne, V., & Hut, R. A. (2017). Flexible clock systems: adjusting the temporal programme. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *372*(1734). https://doi.org/10.1098/rstb.2016.0254

Van Volkinburg, H., & Balsam, P. (2014). Effects of Emotional Valence and Arousal on Time Perception. *Timing & Time Perception (Leiden, Netherlands)*, *2*(3), 360–378. https://doi.org/10.1163/22134468-00002034

Wearden, J. H., & Penton-Voak, I. S. (1995). Feeling the heat: body temperature and the rate of subjective time, revisited. *The Quarterly Journal of Experimental Psychology. B, Comparative and Physiological Psychology*, *48*(2), 129–141. https://doi.org/10.1080/14640749508401443

Wehrman, Sanders, R., & Wearden, J. (2023). What came before: Assimilation effects in the categorization of time intervals. *Cognition*, *234*, 105378. https://doi.org/10.1016/j.cognition.2023.105378

Wiener, M., Thompson, J. C., & Coslett, H. B. (2014). Continuous carryover of temporal context dissociates response bias from perceptual influence for duration. *PloS One*, *9*(6), e100803. https://doi.org/10.1371/journal.pone.0100803

Wittmann, M. (2009). The inner experience of time. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *364*(1525), 1955–1967. http://rstb.royalsocietypublishing.org/cgi/content/abstract/364/1525/1955

Yin, B., Shi, Z., Wang, Y., & Meck, W. H. (2022). Oscillation/Coincidence-Detection Models of Reward-Related Timing in Corticostriatal Circuits. *Timing & Time Perception*, *11*(1-4), 124–166. https://doi.org/10.1163/22134468-bja10057