Acta Psychologica 257 (2025) 105043

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Emotional time lengthening carries over to subsequent neutral events

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ARTICLE INFO

Keywords:
Time perception
Emotion
Valence
Arousal
Vibration
Torso

ABSTRACT

The perceived time can shrink or expand for emotional stimuli. Converging evidence suggests that emotional time distortions are rooted in the emotional states of the timing agents because emotional stimuli can influence the timing of simultaneous neutral events. As emotional states are transitory, we investigated if time modulating emotional states also influence timing of subsequent neutral events. In each trial, we induced different valence and arousal levels by using affective vibrotactile patterns before participants judged the duration of neutral auditory tones. Compared to neutral patterns, affective patterns modulated participants' time perception of the subsequent tones. We observed an interaction between arousal and valence: Pleasant-Low arousal patterns expanded the timing of subsequent neutral events more than Unpleasant-Low arousal patterns while Pleasant and Unpleasant-High arousal led to a similar temporal expansion. Our results indicate time modulating effects of emotional stimuli are due to changed emotional states and influence time perception likely until the underlying state decays.

1. Introduction

Time perception is not veridical and influenced by both external and internal factors. External factors could include the number of elements that we perceive, or their speed in a visual scene (Kaduk et al., 2023). In contrast, emotional state of an agent is an internal factor affecting the perceived time (Droit-Volet, 2019; Gable et al., 2022; Lake et al., 2016; Schirmer, 2011). For instance, emotional faces are perceived to last longer than neutral ones (Droit-Volet et al., 2004; see Lake et al., 2016 for a review). In fact, a great body of research is devoted to understand how valence and/or arousal modulate the perception of time (Droit-Volet, 2019; Droit-Volet & Gil, 2009; Gable et al., 2022; Lake et al., 2016; Schirmer, 2011). Following Russel's circumplex model of emotions (Russell, 1980), studies often define emotional stimuli in two dimensions: valence and arousal. Valence describes pleasantness or unpleasantness whereas arousal indicates the strength or excitement level of an emotion ranging from sleepiness to high alertness. Highly arousing events are typically perceived to last longer than events with lower or middle arousal levels (Gil & Droit-Volet, 2011, 2012; Mella et al., 2011; Noulhiane et al., 2007). Time also expands for pleasant and unpleasant stimuli compared to neutral ones (Droit-Volet & Gil, 2021; Effron et al., 2006; Gil & Droit-Volet, 2012; Lambrechts et al., 2011). Moreover, arousal and valence can interact in their influence on time estimation. For instance, the perceived duration of low arousing events is shorter than that of highly arousing events when they are unpleasant while the opposite is true for pleasant stimuli (Angrilli et al., 1997).

These emotional timing effects are often discussed within the scalar expectancy (timing) theory (SET). According to SET, time perception is governed by an internal clock where an accumulator measures time by accumulating "ticks" that are released by a switch from a pacemaker (Church & Gibbon, 1982; Gibbon et al., 1984). Two mutually non-exclusive accounts of modelling emotion using SET gained traction in the timing literature. The first account suggests that emotional stimuli modulate the opening and closing regime of the switch between pacemaker and accumulator by attracting attention to the timed emotional stimuli (Cavdan et al., 2023; Gil et al., 2009; Lui et al., 2011; Meck & MacDonald, 2007). Due to this change in switch's regime more ticks are accumulated by the accumulator for estimating time. In contrast, the second account suggests that emotional states, particularly arousal, modulate the rate of the pacemaker. This directly affects the number of ticks produced by the pace maker which results in speeding up or slowing down of time independent of the attended stimulus (Burle & Casini, 2001; Cavdan et al., 2023; Gil & Droit-Volet, 2012).

Disentangling these accounts often is not possible as the majority of

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https://doi.org/10.1016/j.actpsy.2025.105043
Received 13 February 2025; Received in revised form 24 April 2025; Accepted 25 April 2025
Available online 16 May 2025

research investigated emotional time modulation by measuring the perceived duration of the emotional-stimuli themselves (Gable et al., 2022; Lake et al., 2016; Schirmer, 2011). This is because, emotional stimuli itself could both attract attention and modulate the pacemaker rate at the same time. Two recent studies attempted to disentangle both accounts by separating emotions from the timed stimuli. Droit-Volet and Gil (2021) asked their participants to reproduce time intervals delineated by two dots which were accompanied by task irrelevant angry or neutral faces. They found that temporal reproductions expanded when there was a simultaneous angry face present during the time interval as opposed to a neutral face. Cavdan et al. (2023) showed a similar emotional modulation in a tactile time reproduction task. They found that tactile reproductions were lengthened when they are accompanied by unpleasant or low arousal sounds. Hence, the current evidence suggests emotional states and not the emotional stimuli themselves influence time judgments (Cavdan et al., 2023; Droit-Volet & Gil, 2021). Thus, the emotional states of the timing agents influence timing in general, including neutral events. Considering that the emotional states may outlast the emotional stimuli themselves, the emotional time modulations could spread and carry over to subsequent events. Therefore, emotional states could continue to alter timing even after the emotional stimuli until they decay or are replaced by another state. Thus, it is an interesting question whether the emotional timing effects are limited to simultaneous timing or extend to other events.

There is at least initial empirical evidence suggesting that lingering emotional states influence the perception of durations. Shi et al. (2012) found that compared to neutral, threatening but not disgusting images lengthen the durations of subsequent events. It is unknown whether this effect is limited to threatening images (unpleasant, high-arousing and avoidance-motivation) or encompasses a wider range of affective states (i.e., pleasant vs. unpleasant and high arousing vs. low arousing). We hypothesize that emotional states defined by arousal and valence will modulate the independent duration estimations of subsequent events. To this end, in a temporal bisection task, participants learned to identify short and long tone durations. They were then asked to sort tones of varying durations by being more similar to short or long tone duration (see Fig. 2).

2. Methods

2.1. Participants

The sample size was determined by a power analysis using G*Power (Faul et al., 2007, 2009) for a two-tailed *t*-test of a medium sized effect (d = 0.5) with 80 % statistical power and α = 0.05. Based on this calculation, 34 participants were recruited and received compensation of 8 €/hour for their participation. During preprocessing of data, two participants were excluded from subsequent analyses due to poor fitting psychometric functions which indicated their inability to distinguish different durations. These participants were replaced by new participants to achieve the intended sample size. The final sample consisted of 9 males and 25 females (Mean Age = 24.8 ± 3.3).The study was approved by the local ethics committee LEK FB 06 (approval No. 2021-0034) in accordance with the declaration of Helsinki (2013) without preregistration.

2.2. Stimulus and apparatus

A commercially available tactile vest (bHaptics TactSuit X40 (bHaptics inc.) was used to generate tactile stimulations. This vest has 40 eccentric rotating mass actuators which deliver ~90 Hz vibrotactile feedback to the mid to upper part of torso in a 5 × 4 array on both back and front side of the torso. The custom vibrotactile patterns were created in a separate pilot study (Goktepe et al., under review) by varying amplitude, frequency and spatio-temporal order of stimulation to evoke emotions with different valence and arousal levels (Seifi et al., 2018; Seifi & MacLean, 2013). Unlike previous studies on affective vibrations, these patterns were used to stimulate the different parts of the front and/or back of upper body as vibration sensitivity varies between the front and back torso (Celebi et al., 2022). Typically, timing studies manipulate emotions with images or familiar sounds which can have semantic connotations or context. In contrast, our vibration patterns do not necessarily have these drawbacks and are potentially more influential as they are felt on the body. We validated the emotionality of our vibrations in a pilot experiment and later in a larger study (reference removed for anonymity). From the patterns tested in the pilot study, we selected five patterns to induce different arousal and valence levels in the current experiment (see Supplementary Materials for details). We selected patterns based on their average normalized rating of arousal and valence. Together with valence and arousal ratings in z-scores, these patterns were: Pleasant-High Arousal (0.55, 1.27, respectively), Pleasant-Low arousal (0.24, -0.76), Unpleasant-High Arousal (-0.18, 1.57), Unpleasant-Low Arousal (-0.26, -1.29), and Neutral-Medium arousal (0.02, -0.04, see Fig. 1 and Supplementary Materials). Briefly, the Pleasant-High Arousal pattern stimulates both sides of the torso by inducing a circular pattern starting from the center of the vest. The Pleasant-Low Arousal pattern is only felt on the back of the torso as a right-to-left swiping motion of two apparently traveling vibrations. The

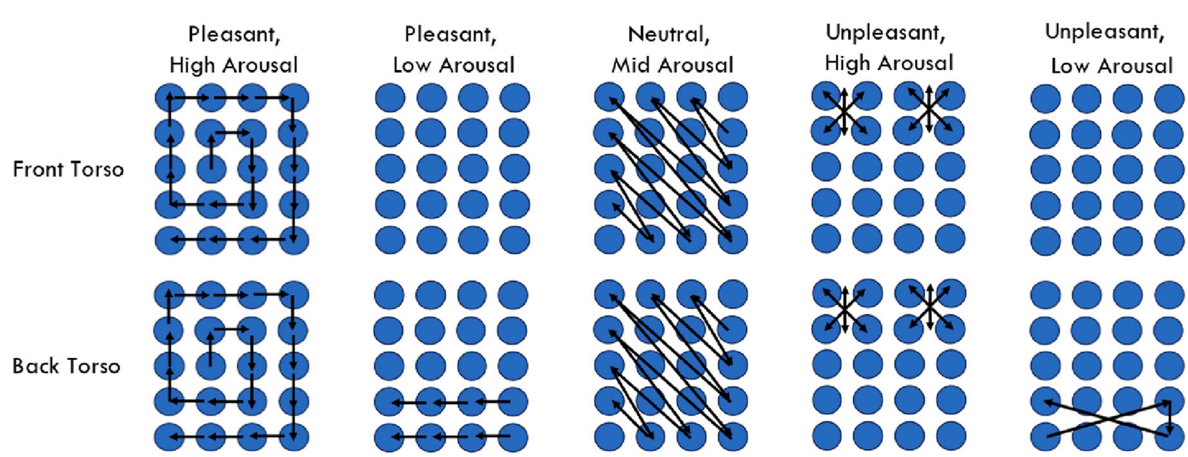

Fig. 1. The selected vibrotactile patterns that are previously rated for arousal and valence. Blue dots depict individual actuators. Vibrotactile patterns are illustrated with arrows showing the direction of each pattern independently from intensity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

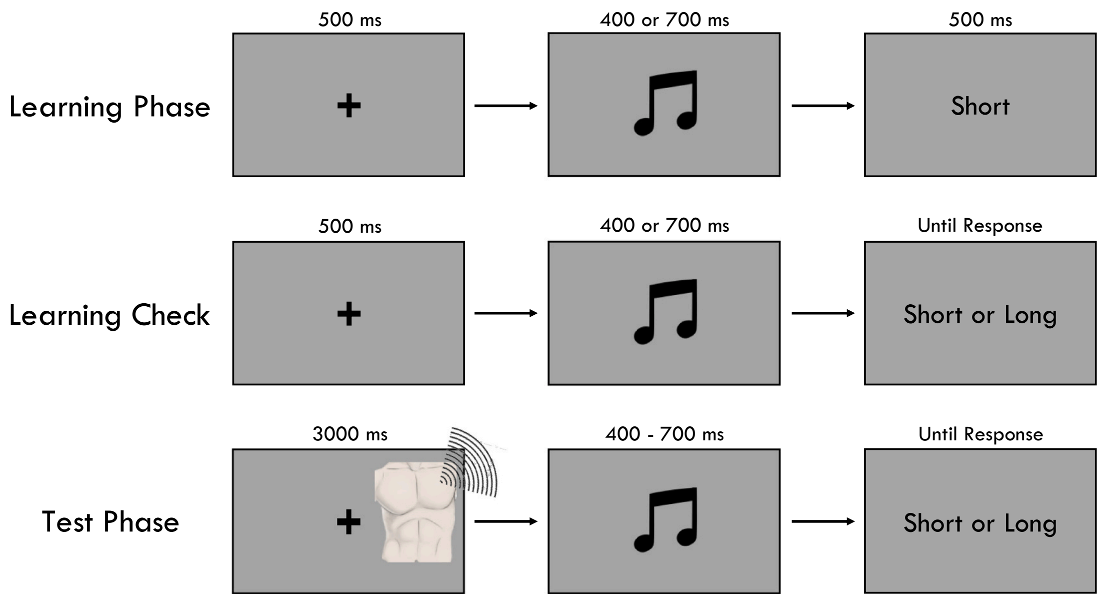

Fig. 2. The experimental procedure as illustrated by example trials from the learning phase, learning check, and test phase. In the learning phase, participants learned the anchor durations by passively listening to the short and long tones. Following the tone offset they received feedback. In the learning check, participants categorized two previously learned anchor duration with feedback on their accuracy. In the test phase, trials started with one of the five vibrotactile patterns accompanied by auditory noise. Following the offset of the vibrotactile pattern an auditory tone played for 400-700 ms. Then, participants categorized the duration of the auditory tone being more similar to short or long anchor duration. The icons were not present in the experiment and are only for illustration purposes.

Unpleasant-High Arousal pattern induced two expansion sensations on the top of the front torso. The Unpleasant-Low Arousal pattern targets the lower portion of the back torso and appears to be a traveling vibration in a horizontal hourglass trajectory. Finally, the Neutral-Mid Arousal pattern follows a diagonal zig-zag trajectory starting from the top right of both sides of the torso. These emotion inducing patterns were applied to participants in standing position, with the haptic vest snugly fit to ensure proper presentation.

The auditory stimuli used for timing judgments were sine-wave sounds with a constant frequency of 400 Hz. In addition, a randomly generated white noise was used to mask the sounds generated by the actuators. Both types of sounds were controlled using Psychtoolbox (Brainard, 1997; Kleiner et al., 2007) and delivered via headphones (Sennheiser Momentum 3). The experiment was conducted using custom scripts programmed in Matlab (MathWorks Inc.).

2.3. Procedure

After signing informing consent, participants put on the tactile vest and stood in front of the experiment computer. Participants then received task instructions before proceeding to the three-part experiment (Fig. 2). In the learning phase, they were trained on short (400 ms) and long (700 ms) auditory tones by passively listening and receiving feedback about the tone durations. The learning trials started with a 500 ms fixation that was followed by an auditory tone with a short or long duration. After listening, participants received immediate feedback about the anchor duration "long" or "short". Once 10 learning trials were completed, they proceeded to the learning check phase. Here, participants listened to short or long tones and were asked to respond whether the tones had been "short" or "long". They received feedback on their performance after each trial. Participants were required to have at least 80 % accuracy in 12 trials before they proceeded to the experiment phase. In the experiment phase, they were asked to perform a temporal bisection task where they had to respond whether different auditory durations (400, 450, 500, 550, 600, 650, and 700 ms) were more similar to the anchored "short" (400 ms) or "long" (700 ms) durations (Fig. 2). Each trial started with the presentation of one of five vibrotactile patterns that was accompanied by a white noise masking the sound generated by the actuators. The onset of white noise always preceded that of the vibrotactile pattern by a random duration between 300 and 500 ms. The offset of the vibrotactile pattern and auditory noise were followed by the to-be-timed auditory stimulus. Following the offset of the auditory stimulus, participants reported whether the duration of the auditory stimulus was closer to the short or long anchor duration. For trials with auditory stimulus durations same as anchor durations, participants received feedback on their accuracy to reinforce anchor durations. Each auditory duration was paired with every vibrotactile pattern, and each pair was repeated 12 times (similar to Shi et al., 2012), yielding 420 trials in total. Hence, the experiment followed a 1 × 5 factorial design within-subjects design (*Patterns:* high arousal pleasant, low arousal pleasant, high arousal unpleasant, low arousal unpleasant, neutral). It was completed in around 45 min including a mandatory break of a minimum of 2 min at the end of the first half of the trials of the test phase.

2.4. Data analysis

For each participant the proportion of long responses (i.e., more similar to long anchor) was calculated for each pair of auditory duration and vibrotactile pattern. Using the proportion long responses, we fitted logistic functions for each pattern condition separately for each participant (Wichmann & Hill, 2001a, 2001b). From the fitted functions the bisection points (*BP*, i.e., duration yielding 50 % long responses) and just-noticeable differences (*JND*, 75 %- discrimination thresholds, i.e., the half width of the interquartile range) were extracted. The Weber fractions (*WF*) were calculated by dividing *BPs* by *JNDs*. To test the emotional effect, we conducted paired samples *t*-tests comparing *BPs* for the mid arousal-neutral pattern with BPs for the remaining patterns of arousal PSEs. We did not correct for multiple comparisons since we are testing independent hypotheses with different independent variables compared to the same variable (García-Pérez, 2023). Using a two-way (*valence*: pleasant, unpleasant × *arousal*: low, high) repeated measures ANOVA we tested how arousal and valence influence subsequent timing judgments. We used Holm-Bonferroni correction for post-hoc tests. To test if the emotional effects alter timing precision and thus violate SET predictions, we conducted paired samples t-tests and a two-way repeated-measures ANOVA (Valence: Pleasant, Unpleasant × Arousal: High, Low) using Weber Fractions computed for each condition. In the result section, mean BPs are reported for the respective conditions with standard errors.

3. Results

The purpose of the experiment was to test whether different emotional states, defined by arousal and valence, influence the timing of subsequent neutral events. To this end, we used vibrotactile patterns eliciting emotional states with different arousal and valence levels to modulate subsequent neutral auditory temporal judgments. Participants performed a temporal bisection task: First, they were trained to discriminate a short auditory tone (400 ms) from a long one (700 ms). These durations served as short and long anchor durations for the test phase. In the test phase, they judged whether auditory tones with durations ranging from the short to long anchors (400, 450, 500, 550, 600, 650, 700 ms) were more similar to the long or the short anchor. Crucially, in the experiment phase, each auditory tone was presented after a task-irrelevant vibrotactile pattern that elicited emotional responses with five arousal and valence levels (Pleasant-Low Arousal, Pleasant-High Arousal, Unpleasant-Low Arousal, Unpleasant-High Arousal, Neutral-Medium Arousal; see Fig. 1 and Methods for details).

We first tested whether timing of neutral auditory tones was modulated by previous emotion-inducing vibrotactile patterns. To this end, we fitted psychometric functions to the proportion of "long" responses for each participant separately for every emotion-inducing pattern as a function of tone duration. From the fitted psychometric functions (see Supplementary Fig. 1 for an example participant), we extracted just-noticeable differences (*JND*) and bisection points (*BPs*). BPs correspond to the tone duration with 0.5 probability of judged to be "long"; JNDs to half the difference of tone durations judged with 0.25 and 0.75 probability as being long. Next, we calculated Weber fractions (*WFs*) as the ratio of JNDs and BPs. We conducted paired samples *t*-tests comparing *BPs* in the baseline condition (pattern eliciting neutral valence and medium arousal, see Fig. 3) to *BPs* in other emotion conditions. (see Fig. 4.)

We found that *BPs* in High Arousal patterns shifted to the left (indicating shorter BPs) compared to the neutral condition (BP = 530.875 ± 8.713). Thus, High Arousal patterns expanded the perceived duration of subsequent neutral tones regardless of being Pleasant, $t(33) = 3.613$, $p < .001$, $d = 0.620$, $BP = 505.151 \pm 6.851$ or Unpleasant, $t(33) = 5.328$, $p < .001$, $d = 0.914$, $BP = 500.968 \pm 6.241$. Further, the Pleasant-Low Arousal pattern also expanded the subsequent timing judgments, $t(33) = 4.239$, $p < .001$, $d = 0.727$, $BP = 505.686 \pm 7.427$. However, the Unpleasant-Low Arousal pattern did not significantly influence subsequent timing, $t(33) = 0.06$, $p = .953$, $d = 0.010$, $BP = 531.205 \pm 8.273$. Overall, these results show that some, but not all emotional stimuli expand the perceived duration of subsequent neutral events.

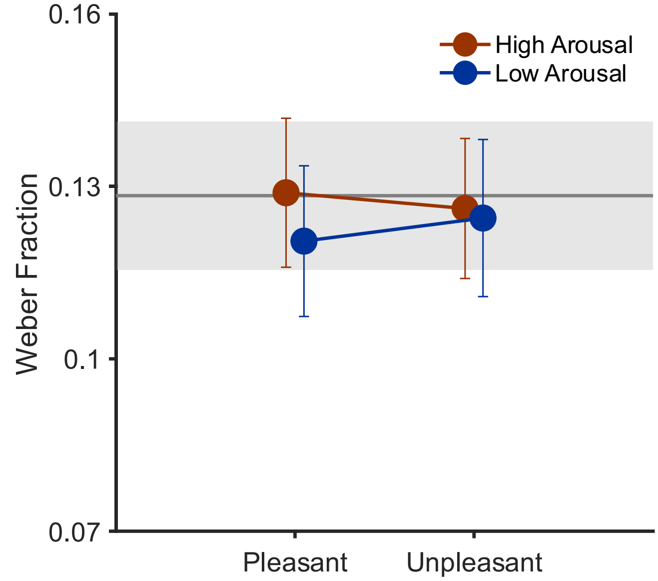

Fig. 4. Average timing sensitivity (WFs) across emotion conditions. The gray line shows the mean timing sensitivity in the baseline (medium arousal/neutral pattern) condition. Error bars and shaded area show 95 % confidence intervals.

Our baseline comparisons hint at an interaction between how arousal and valence jointly modulate subsequent timing. In order to check this,

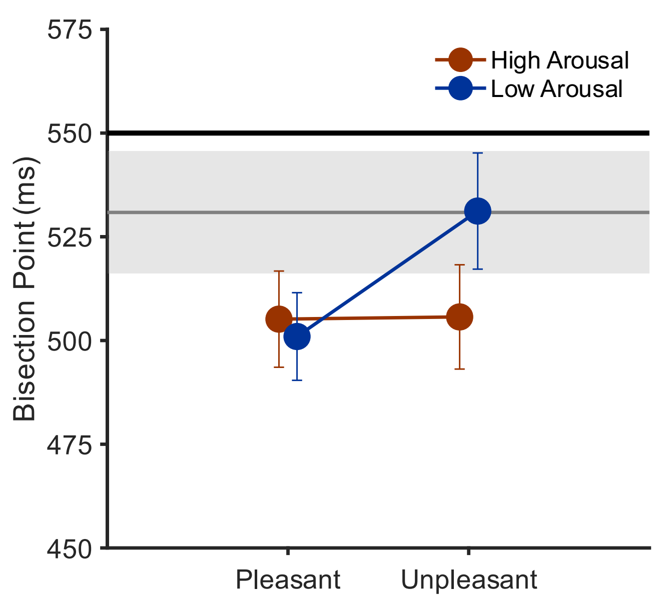

Fig. 3. Average *BPs* across emotion conditions. The black line shows the arithmetic *BP*. The gray line shows the mean bisection point in the baseline (medium arousal/neutral pattern) condition. Error bars and the shaded area show 95 % confidence intervals.

we conducted a two-way repeated measures analysis of variances (ANOVA) on *BPs* (*Valence*: Pleasant, Unpleasant × *Arousal*: High, Low). The valence of the vibrations did not significantly modulate the perceived duration of subsequent tones, $F(1,33) = 3.808$, $p = .060$, $\eta^2 = 0.051$. There was a main effect of arousal indicating that the time expands on average more with carry-over High Arousal than Low Arousal, $F(1,33) = 19.241$, $p < .001$, $\eta^2 = 0.106$. However, there was also a significant interaction between arousal and valence, $F(1,33) = 27.744$, $p < .001$, $\eta^2 = 0.100$ (Fig. 3). Holm-Bonferroni corrected post-hoc tests suggested that time expanded significantly more from Pleasant-Low Arousal and High Arousal patterns than from Unpleasant-Low Arousal pattern (all ps < .001). The remaining comparisons did not reach significance (ps > .5). Together, these results suggest that High compared to Low Arousal yields subsequent time expansion for Unpleasant pattern but not for Pleasant pattern.

Timing precision is often linearly related to the duration of the timed events. That is to say, timing errors linearly increase with duration, which is captured by the WF (Gibbon, 1977). As this linearity in temporal sensitivity is a core tenet of SET (Church & Gibbon, 1982; Gibbon, 1977; Gibbon et al., 1984), we assessed whether the temporal estimations made here follow the same trend, i.e., whether WFs are similar across conditions and independent of BPs. The temporal expansion of tones following the emotional patterns could be explained by an emotional bias or increased temporal precision elicited by emotions. Since in both cases BPs would shift compared to neutral conditions, we can rule out the latter explanation by comparing WFs. In other words, if participants became more or less precise in their temporal judgments due to emotional patterns, this should be reflected in different WFs for neutral and emotional conditions.

We compared the *WF* of auditory temporal estimations in the baseline condition to each of the emotion conditions. None of the four pairwise comparisons reached significance (all *ps* > .14). We also tested the interaction between arousal and valence with respect to WFs. A two-way repeated-measures ANOVA (Valence: Pleasant, Unpleasant × Arousal: High, Low) yielded no significant interaction, $F(1,33) = 1.233$, $p = .275$. That is, temporal precision was not statistically different across conditions, suggesting that effects in BPs cannot be explained by differences in temporal precision.

4. Discussion

Previous studies have shown that temporal judgments are influenced by the emotional valence and arousal of the timed stimuli (Droit-Volet, 2019; Droit-Volet & Gil, 2009; Gable et al., 2022; Lake et al., 2016). Similarly, valence and arousal influence temporal judgments of other independent neutral stimuli that are presented simultaneously (Cavdan et al., 2023; Droit-Volet & Gil, 2021). Moreover, initial evidence indicates that emotional timing effects are not limited to simultaneous timing judgments but also extend to subsequent judgments, at least for threatening events that are less than a second apart from the timed stimulus (Shi et al., 2012). In this study, we showed that low arousal pleasant and high arousal emotional states induced by task irrelevant tactile stimuli can expand subsequent timing of neutral auditory tones by ~5 % in the sub second range. The comparable Weber fractions for neutral and emotional patterns suggest that the lingering emotional states bias neutral timing judgments linearly rather than modulating their precision. Thus, the current results extend carry over emotional timing effects from threatening stimuli to more general emotional states defined by arousal and valence and from tactile to auditory timing. Similarly, the current results extend the evidence on emotional timing effects from the emotional stimuli themselves to the timing of subsequent neutral events.

We found that both low and high arousing patterns expanded the subsequent auditory timing compared to neutral and medium arousing patterns. Our results are in line with previous studies and suggest that temporal expansion by high arousal is not only limited to timing of emotional stimuli themselves (Gil & Droit-Volet, 2012; Gupta & Cummings, 1986; Mella et al., 2011) or timing of neutral stimuli co-occurring with high arousing stimuli (Cavdan et al., 2023). However, it is important to note that not all high arousing stimuli expand the timing of subsequent events. The estimated duration of neutral stimuli expands when it is preceded by a high arousing threatening picture but not by a high arousing disgusting picture (Shi et al., 2012). Also, we found that timing judgments expanded following low arousing pleasant but not low arousing unpleasant patterns compared to neutral patterns. Considering this together with the expansion after high arousing patterns, the carry over timing effect we observed stems from the combination of arousal and valence as evidenced by the interaction between valence and arousal. This is in line with Angrilli et al. (1997), who found a similar interaction between valence or arousal. They proposed two distinct mechanisms for explaining the interaction effect in timing of emotional stimuli. They argued that the timing mechanism for low arousal stimuli is driven by attention whereas timing of high arousal stimuli is driven by emotional arousal leading to increased pulse accumulation.

In line with Angrilli et al. (1997), we found that the duration of auditory tones was overestimated following a Pleasant-Low Arousal pattern but not when they followed an Unpleasant-Low Arousal pattern. In addition, we found that Pleasant-Low Arousal pattern expanded the duration of the subsequent auditory tones compared to Neutral-Mid Arousal pattern. Thus, our results show that not just the timing of Pleasant-Low Arousal stimuli but also timing of subsequent neutral events expands following a Pleasant-Low Arousal stimuli. Angrilli et al. (1997) explains these differences with different processing loads of stimuli, where the higher processing load of unpleasant stimuli leads to overestimation compared to pleasant stimuli with lower loads. Although our results are in line with Angrilli et al. (1997), it is not clear if processing load could account for the timing of subsequent events. That is because the auditory tones should impose similar processing loads since they were separated from the emotion-inducing stimuli (Cavdan et al., 2023). Furthermore, comparing low arousal conditions with the neutral condition revealed a more nuanced picture. The subsequent timing of tones was comparable when it followed an unpleasant or a neutral pattern but overestimated after a pleasant pattern. Therefore, different processing loads could explain the current results by assuming only processing relatively less information influence time judgments or equal processing load for unpleasant and neutral patterns. Finally, Cavdan et al. (2023) did not find an interaction between valence and arousal of auditory tones on the timing of simultaneous neutral tactile stimuli. Therefore, the attention mechanism appears to offer an explanation limited to the timing of emotional stimuli only, which might be short-lived.

Unlike Unpleasant-Low Arousal pattern, we found that high arousal pleasant and unpleasant patterns led to an overestimation of the duration of subsequent neutral tones compared to neutral patterns. Thus, our results associated with high arousal patterns diverge from Angrilli et al. (1997) but replicate and extend previous reports suggesting that time expands more with increasing arousal of the timed stimuli with a certain valence (Droit-Volet et al., 2004; Gil & Droit-Volet, 2012; Mella et al., 2011). However, it is important to note that the stimuli in those studies had similar valence and directly timed. In contrast, Cavdan et al. (2023) asked their participants to reproduce the duration of neutral vibrations presented alongside auditory emotional stimuli. Similarly, they also found that vibrations presented with high-arousal stimuli were perceived to be longer than those paired with low-arousal stimuli. Thus, our results extend the timing effects of arousal from timing of simultaneous neutral events to subsequent neutral events. Furthermore, the only other study on carry over emotional effects (Shi et al., 2012) found high-arousal threat but not disgust pictures to modulate subsequent vibrotactile timing. Thus, together with the current results, it is clear that different combinations of affective properties (i.e., approach vs avoidance, valence, arousal) can interact in their influence on the timing judgments.

In general, time expansion effects of arousal and valence observed here were comparable to most previous studies on the direct timing of emotional stimuli (Gable et al., 2022; Lake et al., 2016), or simultaneous neutral stimuli (Cavdan et al., 2023; Droit-Volet & Gil, 2021). Two mutually non-exclusive explanations have been put forward to explain these effects within the SET framework. While one explanation suggests that the emotional stimuli expand time through capturing attention (not to be confused by the attentional mechanism proposed by Angrilli et al., 1997), the other assumes a change in clock rate during emotional episodes. These explanations are often inseparable in timing tasks involving emotional stimuli, as such stimuli could both attract attention and induce emotions with varying valence and arousal. This also points to the fundamental question whether the time-modulating effect is mainly related to the presentation of emotional stimuli themselves, or to a longer lasting change in emotional state. Our study design sheds light on this question: Our vibrotactile emotional patterns were completely irrelevant to the auditory temporal bisection task. Thus, emotional stimuli were not directly part of the time estimation, yet still affected subsequent timing. Therefore, our results provide evidence suggesting that emotional states themselves influence timing, and that their influence lingers for a while, consistent with a previous study (Shi et al., 2012). We conclude that emotional timing effects do not arise from the timed stimuli or a related attentional deployment, but from the emotional state of the timing agent. The current results cannot be explained directly by attention modulation since the attentional shift caused by emotion would be prior to the timing of the neutral tone. Hence, the attentional accounts should assume a sustained attentional modulation to be compatible with our results. In contrast, the carry-over emotional timing effect seems to be more compatible with extending the clock speed explanation (Gil & Droit-Volet, 2012). It is possible to argue that the emotional vibrotactile patterns in our experiment altered participant's emotional state and accelerated the internal clock speed, i.e., the pacemaker. The altered emotional state then accelerated the pacemaker for some time until it gradually decayed. That is, subsequent tones expanded the subjective time, because the elevated pacemaker speed was sustained for some time after the emotional stimulus. However, our results clearly suggest that not all emotional stimuli result in carry-over timing effects. Thus, if the increased clock speed is responsible for the time modulation, future studies should address which emotional states are capable of increasing the clock speed.

If the clock rate remains elevated until the emotional response decays, this raises the question of how far reaching the emotional timings effects are. It is safe to assume that emotional states are short-lived typically in seconds to minutes range, even when they are not disrupted by other emotional states (Verduyn et al., 2015). In agreement with this, Shi et al. (2012) found that threatening pictures influenced subsequent temporal judgments up to 1000 ms. Longer lasting mood states, influence timing similarly to emotions both in healthy (Chebat et al., 1995; Droit-Volet et al., 2011) and possibly in clinical groups (Droit-Volet, 2013). Thus, it appears emotional effects on timing can spread over time before they decay. The strength of emotions could be a factor determining the rate of this decay.

The current study provided evidence for time-modulating effects of emotional stimuli on the perception of subsequent neutral stimuli. However, it is important to note limiting factors when interpreting the current results. The goal of the experiment was to disentangle the effects of arousal and valence on timing by separating the source of emotion from the timed stimuli. While it is hard to argue that emotional carry over is specific to modality (auditory) we used to measure time perception, its strength might be different for other senses as timing precision varies across senses (Lhamon et al., 1962). Relatedly, the study of time and time perception is susceptible to methodology and design choices. For instance, here, we measured timing in a sub-second range using a bisection task. However, it is not uncommon to observe different timing effects depending on the duration of the timed stimuli (Wearden & Lejeune, 2008). Previous research has generally shown that time perception in the sub-second range primarily relies on automatic processing, while longer durations tend to recruit rather controlled mechanisms (Lewis & Miall, 2003). Thus, future studies need to test if the emotional effects reported here apply to judgment of longer time intervals. Similarly, our findings are based on a temporal bisection task which might produce different results than temporal reproduction. Finally, we used a limited selection of vibrotactile patterns varying in duration that had been validated with a different sample. We used white noise that preceded the patterns by a random duration to alleviate any potential effect of pattern duration on the subsequent timing of tones. We assume that this random offset has counteracted any systematic timing cues that could bias our participants. This assumption is further supported by the result that BPs for Pleasant-Low Arousal and Unpleasant-High Arousal were significantly different, despite those patterns having the same duration. However, future studies could formally test whether the duration of the previous pattern affects subsequent timing and use a wider selection of stimuli, with arousal and valence levels measured in the same sample for which time estimation effects are also assessed.

In conclusion, we showed time modulating effects of emotional stimuli to subsequent temporal judgments of neutral events. More specifically, we found that the duration of neutral auditory tones is overestimated when they were preceded by high arousal stimuli or low arousal unpleasant vibrotactile patterns. The interaction between the arousal and valence might be hinting at how the effect of different emotional states on timing decays over time. Our results are in line with SET and slightly favor the pacemaker modulation explanation of previous emotion effects over the attentional explanation. Overall, we suggest that the emotion related changes in the pacemaker regime gradually decay over time thus allowing the emotional timing effects to carryover to subsequent events.

CRediT authorship contribution statement

Nedim Goktepe: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis. **Müge Cavdan:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Knut Drewing:** Writing – review & editing, Supervision.

Funding

This project was funded by European Union's Horizon 2020 FET Open research programme under grant agreement no 964464 (ChronoPilot). M.C. and K.D. were further supported supported by the German Research Foundation DFG-project no. 502774891-ORA project "UNTOUCH".

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgments

The authors would like to thank Kerstin Mischor who created the vibrotactile patterns and collected data within the framework of her Master thesis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2025.105043.

Data availability

The datasets generated for this study as well as vibrotactile patterns are available at 10.5281/zenodo.14186033.

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