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Discriminative Fear Learners are Resilient to Temporal Distortions during Threat Anticipation

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Abstract

Discriminative fear conditioning requires learning to dissociate between safety cues and cues that predict negative outcomes yet little is known about what processes contribute to discriminative fear learning. According to attentional models of time perception, processes that distract from timing result in temporal underestimation. If discriminative fear learning only requires learning what cues predict what outcomes, and threatening stimuli distract attention from timing, then better discriminative fear learning should predict greater temporal distortion on threat trials. Alternatively, if discriminative fear learning also reflects a more accurate perceptual experience of time in threatening contexts, discriminative fear learning scores would predict less temporal distortion on threat trials, as time is perceived more veridically. Healthy young adults completed discriminative fear conditioning in which they learned to associate one stimulus (CS+) with aversive electrical stimulation and another stimulus (CS-) with non-aversive tactile stimulation and then an ordinal comparison timing task during which CSs were presented as task-irrelevant distractors Consistent with predictions, we found an overall temporal underestimation bias on CS+ relative to CS- trials. Differential skin conductance responses to the CS+ versus the CS- during conditioning served as a physiological index of discriminative fear conditioning and this measure predicted the magnitude of the underestimation bias, such that individuals exhibiting greater discriminative fear conditioning showed less underestimation on CS+ versus CS- trials. These results are discussed with respect to the nature of discriminative fear learning and the relationship between temporal distortions and maladaptive threat processing in anxiety.

Keywords

Duration discrimination; timing and time perception; anxiety; fear conditioning; individual differences; emotion

1. Introduction

You're trying to meet a grant deadline by the end of the day but feel confident that you will be able to submit in time. You then receive an email from your significant other saying he/she would like to speak with you about something important. Based on past experiences,

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you worry that this conversation will be unpleasant. Negative anticipation of this impending discussion may alter your perception of how much time remains to submit the grant, which might, in turn, have adverse consequences for completing the submission. As this example demonstrates, threatening circumstances can change our perceptions of the world around us, affecting not just our experience of a threatening event but also ongoing task relevant processes that may affect behavior and task performance (Allman et al., 2014; Brendel et al., 2014; Buhusi & Meck, 2005).

Distortions in time perception are perceptual phenomena that have frequently been reported both anecdotally and empirically in response to threatening events. Threatening stimuli are typically overestimated in duration, such that they are perceived to last longer than their veridical duration or the duration of a neutral stimulus (e.g., Bar-Haim et al., 2010; Droit-Volet & Meck, 2007; Droit-Volet et al., 2010; Eberhardt et al., this issue; Grommet et al., 2011; Meck, 1983; Tipples, 2011). However, less empirical work has investigated how threatening stimuli affect time perception for task-relevant nonthreatening stimuli. Nonhuman animal research has demonstrated that the anticipation of an aversive foot-shock impairs the ability of rats to simultaneously time two temporal intervals (Meck & MacDonald, 2007), suggesting that the anticipation of threat affects the ability to divide attention. In humans, it has been shown that when emotionally arousing pictures serve as distractors during a timing task, the duration of a neutral, task relevant stimulus is underestimated in duration (Lui et al., 2011). This effect was also attributed to attention and is consistent with attentional models of time perception, which suggest that attentional resources are shared between timing and other cognitive processes, such that when attention is distracted, events are underestimated in duration (Buhusi & Meck, 2009; Matthews & Meck, in press). Nevertheless, a recent investigation suggests that differences in complexity may explain distortions in temporal estimates for emotional versus non-emotional pictures (Folta-Schoofs et al., 2014). Using fear conditioned stimuli, which are neutral stimuli that derive their emotionality from being paired with aversive unconditioned stimuli (US) and thus can be very simple stimuli, affords the opportunity to examine the effects of threatening distractors on time perception for task-relevant stimuli while avoiding potential perceptual confounds.

Fear learning is a critical ability that enables individuals to appropriately identify threat cues and anticipate aversive outcomes. Discriminative fear conditioning is a conditioning procedure wherein an individual learns to discriminate between two neutral conditioned stimuli, one (CS+) that is paired with an aversive unconditioned stimulus and another (CS-) that is not. This procedure has served as an important model for understanding how we learn to discriminate threat cues from neutral events in our environment. It has been implemented primarily to inform our understanding of anxiety disorders, with resulting evidence suggesting that individuals with anxiety experience deficits in discriminating between threatening and neutral stimuli (Craske et al., 2012; Gazendam et al., 2013; Lissek et al., 2005, 2009, 2014). Such deficits are typically demonstrated using physiological measures of implicit learning, such as skin conductance responses (SCRs) and startle reflexes. Nevertheless, the cognitive processes underlying poor threat discrimination and the impact of such deficits on perception remains relatively unexplored.

If physiological measures of threat discrimination exclusively reflect learning cue predictability, that is, learning what stimulus predicts what outcome, and if threats distort time perception, then better discriminative fear learners might be expected to demonstrate exaggerated temporal biases for stimuli presented under learned threat conditions. However, dissociations have been suggested between cue predictability and temporal predictability, that is, *when* an outcome is expected to occur (Davies & Craske, 2015; Lake & LaBar, 2011), and it has been suggested that temporal processing plays an important role in fear conditioning (Gallistel & Gibbon, 2000). Thus, physiological measures of threat discrimination may reflect more than cue predictability, possibly also revealing differences in the veridicality of the perceptual experience of time under conditions of threat, with greater discriminative fear learners more attuned to the temporal relationships between stimuli. If such were the case, better discriminative fear learners might demonstrate less temporal distortion for stimuli presented under threatening conditions.

In this study, we used discriminative fear cues to examine how threat might affect time perception for task relevant neutral stimuli and how this effect might be modulated by individual differences in a physiological measure of threat discrimination. Participants first completed a modified discriminative fear conditioning procedure during which they learned to associate a threat cue with mild electrical stimulation and a neutral cue with non-aversive tactile stimulation. The difference between SCRs to the CS+ and the CS- was calculated as a physiological index of discriminative fear learning. After discriminative fear conditioning, participants completed an ordinal comparison task during which they were instructed to determine whether the second of two tones was longer or shorter in duration than the first. The CS+ and CS- cues were presented between the two tones, with their respective aversive and non-aversive outcomes delivered after the second tone. We predicted that the second tone would be underestimated in duration when preceded by the CS+ versus the CS-, given that participants would be required to time the second tone within the context of an incidental, anticipatory threat cue that was expected to distract attention from timing processes.

Critically, we were interested in testing two competing hypotheses for how individual differences in threat discrimination might modulate temporal distortions in threatening versus neutral contexts. First, if greater physiological evidence of threat discrimination exclusively reflects better learning of cue predictability and if task irrelevant threats are hypothesized to distract attention from timing a task-relevant stimulus, then greater threat discrimination scores would be expected to positively predict the magnitude of temporal underestimation on CS+ versus CS- distractor trials. In other words, greater differences in SCRs to CS+ versus CS- would be associated with shorter temporal estimates for task relevant stimuli on CS+ versus CS- distractor trials. On the other hand, if greater threat discrimination scores reflect a more accurate perceptual experience of time under threatening conditions, then greater threat discrimination would be negatively associated with temporal underestimation. In other words, greater differences in SCRs to CS+ versus CS- would be associated with less underestimation of temporal estimates for task relevant stimuli on CS+ relative to CS- distractor trials.

2. Methods

2.1 Participants

Sixty-one healthy adults provided written informed consent and received monetary compensation ($10/hr) or course credit for participation. We excluded 11 skin conductance non-responders (SCRs observed for ≤ 10% of trials during conditioning) and 4 additional participants for not demonstrating explicit knowledge of cue color/stimulation type pairings, given that such explicit knowledge is argued by some to be critical for successful trace conditioning (Weike et al., 2007), wherein cues are separated from their respective outcomes by an empty interstimulus interval. The final sample consisted of 46 participants (23 females; 18-34 years old, mean age = 20.67; SD = 3.63). The study protocol was approved by the Duke Medical Center Institutional Review Board.

2.2 Stimulus Materials

Stimuli were delivered using Presentation Software (Neurobehavioral Systems, Albany, CA). Tones (400 Hz sine waveforms with 3 ms linearly ramped rise/fall times) were delivered dichotically using BOSE QuietComfort® 15 Acoustic Noise Cancelling® headphones. Blue and green squares (3′ × 3′) signaled threat and neutral trials. All participants completed the trait anxiety scale of the Spielberger State-Trait Anxiety Inventory (Spielberger, 1983).

For each participant, an ascending staircase procedure was used to calibrate the 15-ms aversive shock, delivered to the flexor surface of the dominant wrist, to a level considered "annoying but not painful". The 15-ms non-aversive tactile stimulus (pictured in Fig. 1), a TSP190 Haptic Stimulation Transducer, was delivered to the extensor surface of the dominant wrist. The device deploys a metal plunger that mechanically stimulates a 1.5 mm diameter surface area of skin and was calibrated to minimize plunger force while ensuring reliable perception. Reinforcer delivery and SCRs were measured using a MP-150 BIOPAC system (Goleta, CA).

2.3 Conditioning Task and Procedure

Participants were pseudo-randomly presented with 10 blue and 10 green squares (3000 ms in duration) (Fig. 1A). One square color was paired with the shock US at a 50% rate. The other square color was paired with the non-aversive tactile stimulation at a 50% rate. All other square presentations were not paired with stimulation. A partial reinforcement schedule was implemented because this procedure has been shown to be more resistant to habituation of orienting responses to CSs than continuous reinforcement (Kaye & Pearce, 1984). Partial reinforcement also allowed us to deconfound the effects of threat anticipation from the effects of US delivery on timing performance in the timing task, as we only looked at timing performance on trials that were not followed by reinforcement. Stimulation was delivered pseudo-randomly 700-1500 ms after the offset of the blue/green square (to approximate the interstimulus intervals in the subsequent timing task). Cue color/stimulation type pairings were counterbalanced between subjects. A 9-12 s jittered fixation period followed each trial. Typical discriminatory conditioning paradigms pair one stimulus (CS+) with an aversive event, while another stimulus (CS-) remains unpaired. In the current study, we paired the

CS- with a non-aversive outcome at the same rate as the CS+ was paired with an aversive outcome. This procedural decision was made to control for general anticipatory effects, in order to more specifically capture threat-related effects, as well as to increase discrimination difficulty between threat and neutral trials. Trace conditioning, in general, is thought to require timing processes for anticipating the US more so than delay conditioning, wherein the offset of the CS and onset of the US are contiguous (Knight et al., 2004). The increased timing demands evoked by the use of trace conditioning with a variable ISI were important for eliciting sufficient variability to use the difference in SCRs to the CS+ and CS- as an individual difference measure. Varying the CS-US interval allowed us to further increase timing demands, which we believed were likely to contribute to individual differences in discriminative fear learning.

To increase attention to cue color/stimulation type contingencies, participants were instructed to indicate, as quickly as possible upon the presentation of a colored square, if they expected to receive the aversive US, the non-aversive tactile stimulation, or were unsure. Participants were informed that the cue color/ stimulation type pairing would not change during the experiment. After conditioning, participants rated how the reinforcers made them feel on 9-point Likert scales of arousal (1 = completely unaroused, 9 = completely aroused) and valence (1 = completely unhappy, 9 = completely happy).

2.4 Timing Task and Procedure

After the conditioning phase, participants completed an ordinal-comparison timing task (Fig. 1B). After an intertrial interval of 3000 ms, each trial began with a standard tone (400 ms). The CS+ or CS- (blue/green square) was presented 400-600 ms after the standard tone offset for 3000 ms. Test tones (200, 300, 400, 500 or 600 ms) were presented 400-600 ms after cue offset. Reinforcement was delivered for each CS type (CS+, CS-) at test tone offset on 50% of trials. After a variable wait period (1500-1700 ms after test tone offset), a response screen prompted participants to judge whether the test tone was ‘longer’ or ‘shorter’ in duration than the standard. The response screen was displayed for 3000 ms. Participants completed 4 practice trials without stimulation to ensure they understood the task. A total of 80 CS+ and 80 CS- trials were presented. For both trial types, each test tone duration was presented 16 times. The task was divided into 4 equal runs. After the timing task, participants were again asked to rate the aversive US and non-aversive tactile stimulation on 9-point Likert scales of arousal and valence.

2.5 Timing Performance Analysis

The proportion of ‘long’ responses given for each test tone duration and CS trial type combination was calculated for each participant. Point of subjective equality scores (PSEs), collected as a measure of temporal bias, and Weber fraction (WF) values, collected as a measure of temporal precision, were calculated from these raw scores using a maximum likelihood function to fit logistic functions to individual participant data. Only trials unpaired with stimulation were included in analyses to remove the potential confound of stimulation delivery on perception or decision-making. Underestimation is reflected by PSE scores > 400 ms, and overestimation is reflected by PSE scores < 400 ms, where 400 ms is the point of objective equality (equal to the actual duration of the first tone). Paired t-tests were conducted to compare PSE and Weber fraction values on threat versus neutral trials.

2.6 Skin Conductance Responses (SCRs) Analyses

SCRs were recorded from the hypothenar eminence of the nondominant hand. SCRs were calculated with the Autonomate analysis program (Green et al., 2014) in MATLAB (MathWorks, Natick, MA) using the criteria reported by Dunsmoor et al. (2009). SCRs were considered responses and their peak amplitude was recorded if the trough-to-peak occurred 1-4 s after stimulus onset, the response lasted 0.5-5.0 s, and the peak amplitude was >0.02 microsiemens. SCRs that did not meet these criteria were scored as zeros. SCRs were manually verified by a trained scorer. SCRs were range-corrected separately for conditioning and timing phases by dividing responses by the largest recorded SCR in that phase per subject (Lykken & Venables, 1971). Discriminative fear learning scores were calculated as the difference between peak amplitude SCRs to CS+ and CS- trials during the conditioning phase, with larger differences reflecting physiological evidence of greater discrimination abilities. Paired t-tests were conducted on peak amplitude SCRs in response to CS+s and CS-s during the conditioning phase and testing phase as evidence of overall discrimination fear learning across participants.

2.7 Correlation and Regression Analyses

A correlation between threat discrimination scores and PSE differences between CS+ and CS- trials was conducted as an *a priori* planned comparison. Given that anxiety has previously been shown to modulate threat-related temporal distortions and given recent evidence that gender may differentially influence emotion-driven temporal distortions (Schirmer et al., this issue), we conducted an additional exploratory stepwise regression with PSE differences scores as the dependent variable and threat discrimination scores, trait anxiety, and gender as independent variables to assess whether PSE differences between CS + and CS- trials could be better explained by including these other independent variables in our model.

One potential confound in this design is the amount of SCR recovery after threat trials, which may have indirectly affected SCRs on subsequent neutral trials. To rule out the contribution of this potential confound, we first calculated average SCRs for neutral trials that were preceded by neutral trials and for neutral trials that were preceded by threat trials. We then calculated the difference between these averages and used this variable along with trait anxiety and gender as independent variables in an exploratory multiple regression analysis predicting discriminative fear learning scores. If this trial sequence measure predicted threat discrimination scores, it would suggest that individual differences in recovery from threat trials affected threat discrimination scores.

3. Results

3.1 Subjective Ratings of the Reinforcers

Participants indicated that they were more aroused and less happy after receiving the aversive shock relative to the non-aversive tactile stimulation, for both the conditioning and timing task phases (all p's < 0.001; Table 1). There were no significant differences in ratings between the two phases, except that participants indicated they were less happy after receiving the shocks during the timing task phase relative to the earlier conditioning phase, $t(45) = 2.54$, $p = 0.015$, *Hedge's* $g_{av} = 0.37$.

3.2 Skin Conductance Responses

Average range-corrected CS+ and CS- SCRs for the conditioning and timing task phases are shown in Fig 2. SCRs were significantly larger in response to CS+s versus CS-s during conditioning, $t(45) = 5.804$, $p < 0.001$, *Hedge's* $g_{av} = 0.80$, indicating discriminative fear learning in the overall sample. The difference between CS+ and CS- SCRs remained significant during the timing task, $t(45) = 3.705$, $p = 0.001$, *Hedge's* $g_{av} = 0.68$.

3.3 Timing Task Performance: Planned Comparisons

Average response functions for CS+ and CS- trials are presented in Fig 3 and average PSE and WF scores are reported in Table 2. CS+ PSE scores were significantly higher than CS- PSE scores, $t(45) = -2.192$, $p = 0.034$, *Hedge's* $g_{av} = 0.38$, indicating, as predicted, that the second tone was underestimated in duration when preceded by the CS+ versus the CS-. There was no difference in WF values between CS+ versus CS- trials, and thus temporal precision was not altered by CS type. However, more than one-third of participants had average WF values < 0.02, suggesting there may not have been enough variability in WF values to capture differences across conditions. The planned correlation between PSE difference scores and threat discrimination scores (SCRs for CS+ versus CS- trials) was significant, $r = -0.313$, $p = 0.034$ (Fig. 4), demonstrating that as threat discrimination scores increased, the temporal underestimation bias on CS+ versus CS- trials was reduced.

3.4 Exploratory analyses

Threat discrimination scores, gender, and trait anxiety were used in a stepwise regression analysis to predict PSE difference scores to determine if the correlation between threat discrimination scores and PSE differences may have been driven or partially explained by other independent variables. The resulting prediction model only contained threat discrimination scores, suggesting that gender and trait anxiety could not significantly explain variance in PSE difference scores and confirming the results of our planned correlation between threat discrimination scores and PSE difference scores. We also ran a multiple regression analysis with discriminative fear learning scores as the dependent measure and trait anxiety, gender, and the difference between average SCRs on neutral trials preceded by threat versus neutral trials as independent variables. This model did not significantly predict discriminative fear learning scores, $F(3,42) = 0.834$, $p = 0.483$, $R^2 < 0.056$. None of the independent variables significantly predicted discriminative fear learning scores (trial sequence SCR difference, $p = 0.12$; trait anxiety, $p = 0.91$; gender, $p = 0.71$). Most importantly, this result suggests that individual differences in threat discrimination scores were not driven by individual differences in SCR recovery as a trial sequence effect (i.e., comparing CS- trials preceded by CS+ versus CS- trials).

4. Discussion

As predicted, we found that learned threat cues resulted in temporal underestimation for task-relevant stimuli. This finding is consistent with the available literature on emotional distractor effects on task-relevant processing (Halbertsma & van Rijn, this issue; Lui et al., 2011) and attentional models of time perception (Buhusi & Meck, 2009; Zakay, 1989), which suggest that attentional resources for timing must be shared with other cognitive processes, such that attentional distraction from timing results in temporal underestimation. This underestimation bias suggests that threat modulates the perception of task-relevant stimuli, which could have important consequences for task performance.

We also demonstrated that the magnitude of this temporal underestimation effect was correlated with discriminative fear learning scores, such that better discrimination of threat versus neutral cues was associated with a reduction in the underestimation bias. This novel finding is in line with the idea that threat discrimination scores do not solely reflect cue predictability, but may also reflect a more accurate perceptual experience of time under threatening conditions, which may have enhanced the learning of stimulus relationships during discriminative fear learning, reflected in greater threat discrimination scores, and reduced biases in time perception on threat trials for individuals with higher threat discrimination scores. This resiliency to threat-related time distortions may be an adaptive consequence of fear learning. For example, a more accurate estimate of the duration of a stimulus presented during the anticipation of an aversive outcome may allow greater accuracy in predicting when that outcome will occur.

These findings suggest that future research is warranted to better understand what processes may contribute to individual differences in discriminative fear learning and how such differences might affect perception. We suggest that the resilience to threat-related time distortions in better discriminative fear learners may support the role of temporal processing in fear conditioning, as it establishes a relationship between better discriminative fear learning and more veridical temporal estimates. Better discriminative fear learning, particularly in the context of a varying CS-US interval as was used in the current study, may reflect the ability to adaptively incorporate knowledge of the distribution of interstimulus interval durations to better learn the relationship between CS and US. Such an interpretation is consistent with Bayesian approaches to understanding time perception, which have suggested that individuals can incorporate sensory information and previously experienced durations into a learned distribution of temporal intervals in order to minimize the effects of noisy sensory input and enhance the precision of duration estimates within a given context (Shi et al., 2013), particularly when doing so would provide a functional advantage (Cicchini et al., 2012).

It is important to note that while threat discrimination scores varied across participants, all the participants included in our analyses reported explicit knowledge of the relationship between the cues and their respective outcomes. This fact further supports our assertion that individual differences in threat discrimination scores may reflect more than explicit cue predictability. The relationship between contingency awareness and physiological conditioning has long been a topic for debate within the conditioning literature (e.g., Lovibund & Shanks, 2002; Manns et al., 2002; Wiens & Öhman, 2002; Shanks & Lovibund, 2002), largely centered on whether physiological conditioning can occur in the absence of awareness. Typical human fear conditioning paradigms have used a fixed CS-US interval duration. Our conditioning procedure differed from these procedures in that we used a variable interstimulus interval between the CS and US, which may have made learning temporal relationships a more important part of discriminative learning and contributed to the difference between explicit and implicit measures of discriminative fear learning in this study. Our physiological measure of discriminative fear learning may thus have been a more nuanced measure of learning than reports of contingency awareness. Given that threat cues outside of a laboratory context are less fixed in their temporal predictive power than typical conditioning procedures, we believe our procedure may provide a more ecologically valid measure of threat discrimination. Our findings suggest that further research using ecologically valid CS and US relationships is warranted to better understand the nature of threat discrimination, particularly acknowledging that our current conclusions are based on a correlational rather than causal relationship.

Although we did not observe a relationship between trait anxiety and discriminative fear learning scores in our healthy participant sample, our findings have potential implications for the study of anxiety disorders. Individuals suffering from anxiety reliably show impairments in the discrimination of threat from nonthreatening cues (e.g., Craske et al., 2012; Gazendam et al., 2013; Lissek et al., 2005, 2009, 2014; Waters et al., 2009). At the same time, studies of time perception have demonstrated exacerbated temporal biases under threatening conditions for individuals with anxiety and phobias (e.g., Bar-Haim et al., 2010; Buetti & Lleras, 2012; Jusyte et al., 2015; Tipples, 2011; Watts & Sharrock, 1984). The novel relationship we observed between threat discrimination abilities and biases in time perception suggests that these previous findings in the clinical anxiety literature could be linked mechanistically. The intolerance of uncertainty has been associated with greater worry, which is a key component of generalized anxiety disorder (e.g., Dugas et al., 1998, 2001; Ladouceur et al., 1997, 1999). Temporal unpredictability is also known to increase anxious responding in individuals suffering from panic disorder and post-traumatic stress disorder (e.g., Grillon et al., 2008, 2009; Simmons et al., 2013). If individuals with anxiety are less able to use temporal information in threatening contexts, they might demonstrate impairments in the ability to learn the relationship between cues predictive of threat and aversive outcomes, such that aversive outcomes are perceived as more unpredictable, which, in turn, might further enhance feelings of anxiety and worry. In the current study, the relationship between threat learning and temporal distortions that we observed in healthy subjects was correlational in nature. Further investigation is necessary to more directly test the possibility that psychopathological deficits, such as overgeneralization of conditioned fear or heightened anticipatory anxiety, may be mediated by inaccuracies in timing and time perception under threatening circumstances or surprise (e.g., Allman & Meck, 2012; Lake & LaBar, 2011; Meck, 2006).

References

Allman MJ, Meck WH. Pathophysiological distortions in time perception and timed performance. Brain. 2012; 135:656–677. DOI: 10.1093/brain/awr210 [PubMed: 21921020]

Allman MJ, Teki S, Griffiths TD, Meck WH. Properties of the internal clock: First- and second-order principles of subjective time. Annu Rev Psychol. 2014; 65:743–771. DOI: 10.1146/annurev-psych-010213-115117 [PubMed: 24050187]

Bar-Haim Y, Kerem A, Lamy D, Zakay D. When time slows down: The influence of threat on time perception in anxiety. Cogn Emot. 2010; 24:255–263.

Brendel E, Hecht H, DeLucia PR, Gamer M. Emotional effects on time-to-contact jydgments: Arousal, threat, and fear of spiders modulate the effect of pictoral content. Exp Brain Res. 2014; 232:2337–2347. DOI: 10.1007/s00221-014-3930-0 [PubMed: 24756860]

Buetti S, Lleras A. Perceiving control over aversive and fearful events can alter how we experience those events: An investigation of time perception in spider-fearful individuals. Front Psychol. 2012; 3:337. [PubMed: 23060824]

Buhusi CV, Meck WH. What makes us tick? Functional and neural mechanisms of interval timing. Nat Rev Neurosci. 2005; 6:755–765. DOI: 10.1038/nrn1764 [PubMed: 16163383]

Buhusi CV, Meck WH. Relative time sharing: New findings and an extension of the resource allocation model of temporal processing. Philos Trans R Soc Lond B. 2009; 364(1525):1875–1885. DOI: 10.1098/rstb.2009.0022 [PubMed: 19487190]

Cicchini GM, Arrighi R, Cecchetti L, Giusti M, Burr DC. Optimal encoding of interval timing in expert percussionists. J Neurosci. 2012; 32(3):1056–1060. DOI: 10.1523/JNEUROSCI.3411-11.2012 [PubMed: 22262903]

Craske MG, Wolitzky-Taylor KB, Mineka S, Zinbarg R, Waters AM, Vrshek-Schallhorn S, Ornitz E. Elevated responding to safe conditions as a specific risk factor for anxiety versus depressive disorders: Evidence from a longitudinal investigation. J Abnorm Psychol. 2012; 121(2):315–324. DOI: 10.1037/a0025738 [PubMed: 21988452]

Davies CD, Craske MG. Psychophysiological responses to unpredictable threat: Effects of cue and temporal unpredictability. Emotion. 2015; 15(2):195–200. DOI: 10.1037/emo0000038 [PubMed: 25603130]

Droit-Volet S, Meck WH. How emotions colour our perception of time. Trends Cogn Sci. 2007; 11:504–513. DOI: 10.1016/j.tics.2007.09.008 [PubMed: 18023604]

Droit-Volet S, Mermillod M, Cocenas-Silva R, Gil S. The effect of expectancy of a threatening event on time perception in human adults. Emotion. 2010; 10(6):908–914. [PubMed: 21171761]

Dugas MJ, Gagnon F, Ladouceur R, Freeston MH. Generalized anxiety disorder: A preliminary test of a conceptual model. Behav Res Ther. 1998; 36(2):215–226. [PubMed: 9613027]

Dugas MJ, Gosselin P, Ladouceur R. Intolerance of uncertainty and worry: Investigating specificity in a nonclinical sample. Cogn Ther Res. 2001; 25(5):551–558.

Dunsmoor JE, Mitroff SR, LaBar KS. Generalization of conditioned fear along a dimension of increasing fear intensity. Learn Mem. 2009; 16(7):460–469. [PubMed: 19553384]

Eberhardt LV, Huckauf A, Kliegl KM. Effects of neutral and fearful emotional states on duration estimation of neutral and fearful face stimuli. Timing Time Percept. (this issue).

Folta-Schoofs K, Wolf OT, Treue S, Schoofs D. Perceptual complexity, rather than valence or arousal accounts for distracter-induced overproductions of temporal durations. Acta Psychol (Amst). 2014; 147:51–59. DOI: 10.1016/j.actpsy.2013.10.001 [PubMed: 24161200]

Gallistel CR, Gibbon J. Time, rate, and conditioning. Psychol Rev. 2000; 107:289–344. [PubMed: 10789198]

Gazendam FJ, Kamphuis JH, Kindt M. Deficient safety learning characterizes high trait anxious individuals. Biol Psychol. 2013; 92(2):342–352. [PubMed: 23174693]

Green SR, Kragel PA, Fecteau ME, LaBar KS. Development and validation of an unsupervised scoring system (Autonomate) for skin conductance response analysis. Int J Psychophysiol. 2014; 91(3):186–193. [PubMed: 24184342]

Grillon C, Lissek S, Rabin S, McDowell D, Dvir S, Pine DS. Increased anxiety during anticipation of unpredictable but not predictable aversive stimuli as a psychophysiologic marker of panic disorder. Am J Psychiatry. 2008; 165(7):898–904. [PubMed: 18347001]

Grillon C, Pine DS, Lissek S, Rabin S, Bonne O, Vythilingam M. Increased anxiety during anticipation of unpredictable aversive stimuli in posttraumatic stress disorder but not in generalized anxiety disorder. Biol Psychiatry. 2009; 66(1):47–53. [PubMed: 19217076]

Grommet EK, Droit-Volet S, Gil S, Hemmes NS, Baker AH, Brown BL. Time estimation of fear cues in human observers. Behav Process. 2011; 86(1):88–93.

Halbertsma H, van Rijn H. An evaluation of the effect of auditory emotional stimuli on interval timing. Timing Time Percept. (this issue).

Jusyte A, Schneidt A, Schönenberg M. Temporal estimation of threatening stimuli in social anxiety disorder: Investigation of the effects of state anxiety and fearfulness. J Behav Ther Exp Psych. 2015; 47:25–33.

Kaye H, Pearce JM. The strength of the orienting response during Pavlovian conditioning. J Exp Psychol Anim Behav Process. 1984; 10:90–109. [PubMed: 6707583]

Knight DC, Cheng DT, Smith CN, Stein EA, Helmstetter FJ. Neural substrates mediating human delay and trace fear conditioning. J Neurosci. 2004; 24:218–228. [PubMed: 14715954]

Ladouceur R, Dugas MJ, Freeston MH, Rheaume J, Blais F, Boisvert JM, Thibodeau N. Specificity of generalized anxiety disorder symptoms and processes. Behav Ther. 1999; 30:191–207.

Ladouceur R, Talbot F, Dugas MJ. Behavioral expressions of intolerance of uncertainty in worry. Experimental findings Behav Modif. 1997; 21(3):355–371. [PubMed: 9243960]

Lake JI, LaBar KS. Unpredictability and uncertainty in anxiety: A new direction for emotional timing research. Front Integr Neurosci. 2011; 5:55. [PubMed: 21954380]

Lissek S, Kaczkurkin AN, Rabin S, Geraci M, Pine DS, Grillon C. Generalized anxiety disorder is associated with overgeneralization of classically conditioned fear. Biol Psychiatry. 2014; 75(11): 909–915. [PubMed: 24001473]

Lissek S, Powers AS, McClure EB, Phelps EA, Woldehawariat G, Grillon C, Pine DS. Classical fear conditioning in the anxiety disorders: A meta-analysis. Behav Res Ther. 2005; 43(11):1391–1424. [PubMed: 15885654]

Lissek S, Rabin SJ, McDowell DJ, Dvir S, Bradford DE, Geraci M, Grillon C. Impaired discriminative fear-conditioning resulting from elevated fear responding to learned safety cues among individuals with panic disorder. Behav Res Ther. 2009; 47(2):111–118. [PubMed: 19027893]

Lovibond PF, Shanks DR. The role of awareness in Pavlovian conditioning: Empirical evidence and theoretical implications. J Exp Psychol Anim Behav Process. 2002; 28(1):3–26. DOI: 10.1037/0097-7403.28.1.3 [PubMed: 11868231]

Lui MA, Penney TB, Schirmer A. Emotion effects on timing: Attention versus pacemaker accounts. PLoS One. 2011; 6(7):e21829. [PubMed: 21799749]

Lykken DT, Venables PH. Direct measurement of skin conductance: A proposal for standardization. Psychophysiology. 1971; 8(5):656–672. [PubMed: 5116830]

Manns JR, Clark RE, Squire LR. Standard delay eyeblink classical conditioning is independent of awareness. J Exp Psychol Anim Behav Process. 2002; 28(1):32–37. DOI: 10.1037/0097-7403.28.1.32 [PubMed: 11868232]

Matthews WJ, Meck WH. Temporal cognition: Connecting subjective duration to perception, attention, and memory. Psychol Bull. (in press).

Meck WH. Selective adjustment of the speed of internal clock and memory processes. J Exp Psychol Anim Behav Process. 1983; 9:171–201. DOI: 10.1037/0097-7403.9.2.171 [PubMed: 6842136]

Meck WH. Frontal cortex lesions eliminate the clock speed effect of dopaminergic drugs on interval timing. Brain Res. 2006; 1108:157–167. doi:10.1016j.brainres.2006.06.046. [PubMed: 16844101]

Meck WH, MacDonald CJ. Amygdala inactivation reverses fear's ability to impair divided attention and make time stand still. Behav Neurosci. 2007; 121:707–720. DOI: 10.1037/0735-7044.121.4.707 [PubMed: 17663596]

Shanks DR, Lovibond PF. Autonomic and eyeblink conditioning are closely related to contingency awareness: Reply to Wiens and Öhman (2002) and Manns et al (2002). J Exp Psychol Anim Behav Process. 2002; 28(1):38–42. DOI: 10.1037/0097-7403.28.1.38 [PubMed: 11868233]

Shi Z, Church RM, Meck WH. Bayesian optimization of time perception. Trends Cogn Sci. 2013; 17:556–564. DOI: 10.1016/j.tics.2013.09.009 [PubMed: 24139486]

Schirmer A, Ng T, Escoffier N, Penney TB. Emotional voices slow down time: Behavioral and neural correlates. Timing Time Percept. (this issue).

Simmons AN, Flagan TM, Wittmann M, Strigo IA, Matthews SC, Donovan H, Paulus MP. The effects of temporal unpredictability in anticipation of negative events in combat veterans with PTSD. J Affect Disord. 2013; 146(3):426–432. [PubMed: 22910447]

Spielberger, CD. Manual for the State-Trait Anxiety Inventory STAI (Form Y). Palo Alto, CA: Consulting Psychologists Press; 1983.

Tipples J. When time stands still: Fear-specific modulation of temporal bias due to threat. Emotion. 2011; 11(1):74–80. [PubMed: 21401227]

Watts FN, Sharrock R. Fear and time estimation. Percept Mot Skills. 1984; 59(2):597–598. [PubMed: 6514503]

Weike AI, Schupp HT, Hamm AO. Fear acquisition requires awareness in trace but not delay conditioning. Psychophysiology. 2007; 44(1):170–180. [PubMed: 17241153]

Wiens S, Öhman A. Unawareness is more than a chance event: Comment on Lovibond and Shanks (2002). J Exp Psychol Anim Behav Process. 2002; 28(1):27–31. DOI: 10.1037/0097-7403.28.1.27 [PubMed: 11868230]

Zakay, D. Subjective time and attentional resource allocation: An integrated model of time estimation. In: Levin, I.; Zakay, D., editors. Time and human cognition: a life span perspective. Amsterdam; North Holland: 1989. p. 365-397.

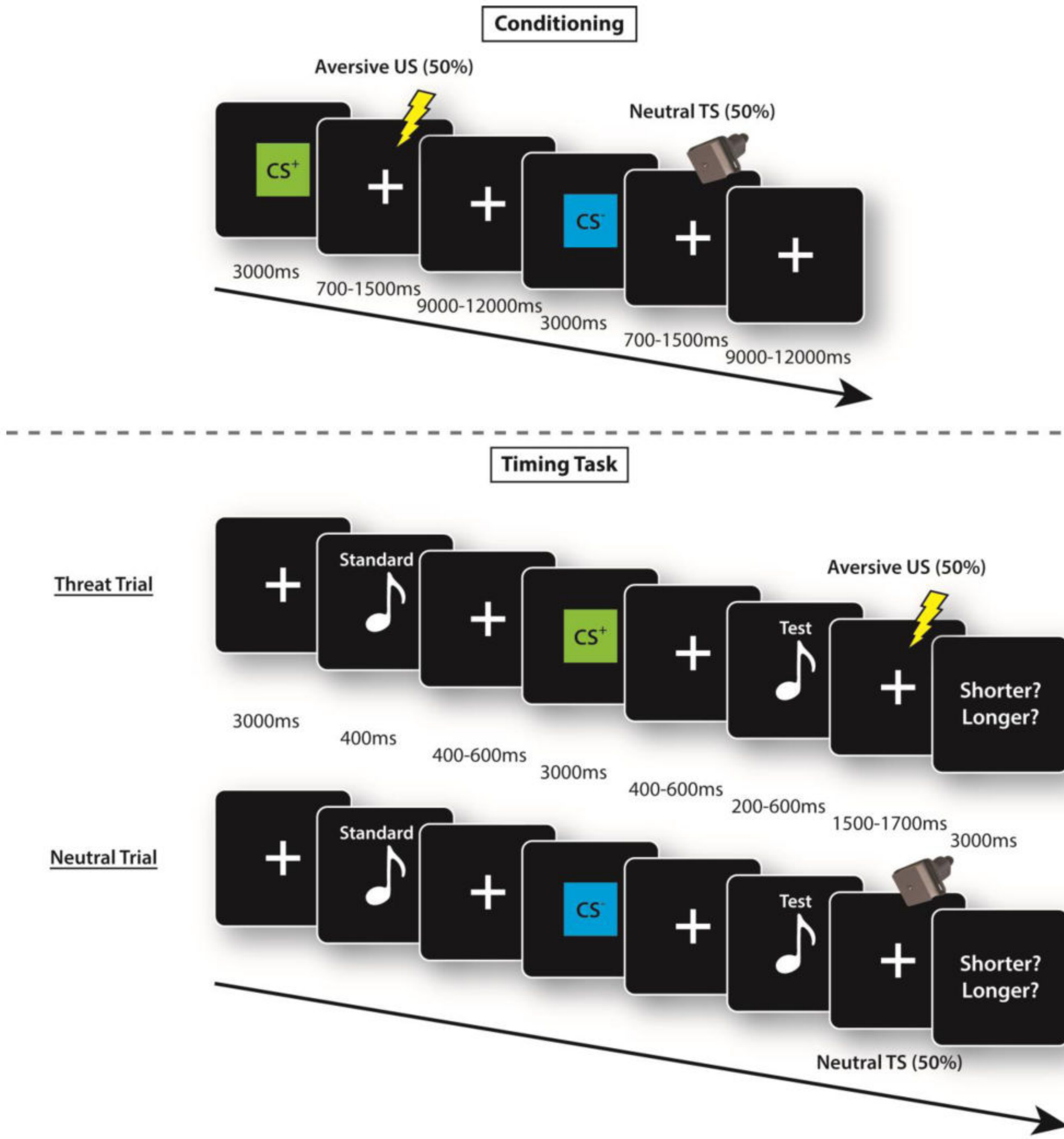

Figure 1.

Example trial sequences for conditioning and timing phases. (A) Conditioning Phase: Green and blue squares were followed by either aversive electrical stimulation (US) or neutral tactile stimulation (TS) on 50% of trials after a variable 700-1500 ms trace interval. Participants were instructed to indicate via key press whether they expected the US, TS, or were unsure as soon as a square was presented. (B) Timing Task: A 400-ms standard tone was presented, followed by one of the two colored squares from the conditioning phase, and then a test tone of varying duration. Stimulation (US or TS) was delivered at the offset of the second tone on 50% of trials. A response screen asked participants to indicate whether the test tone was ‘longer’ or ‘shorter’ in duration than the standard tone.

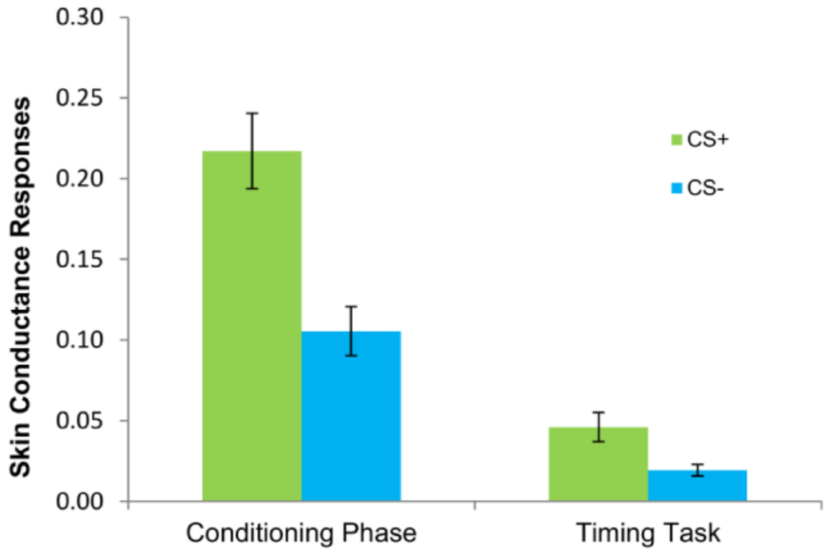

Figure 2.
Average range-corrected skin conductance responses (SCRs) during the conditioning phase and timing task. SCRs were significant larger for CS+ versus CS- trials during the conditioning and timing task phase. Error bars reflect standard error of the mean.

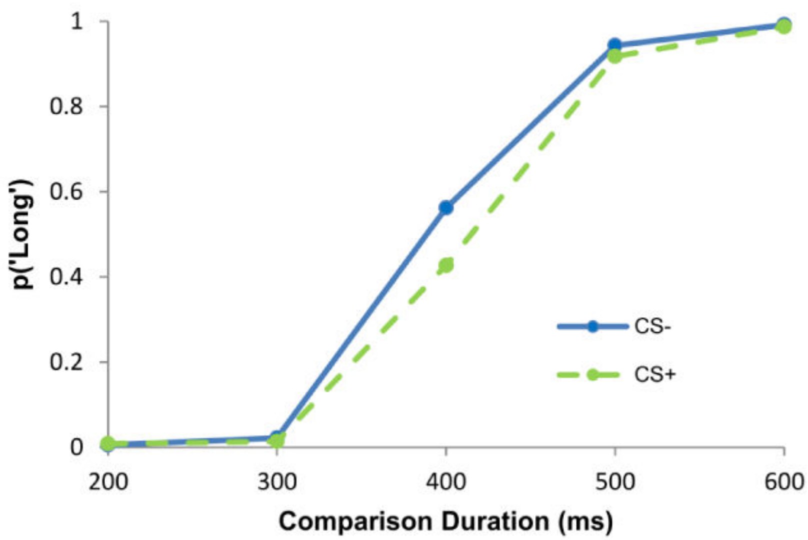

Figure 3.

Average proportions of long responses made for each comparison duration on CS+ and CS- trials demonstrates the underestimation bias on CS+ trials.

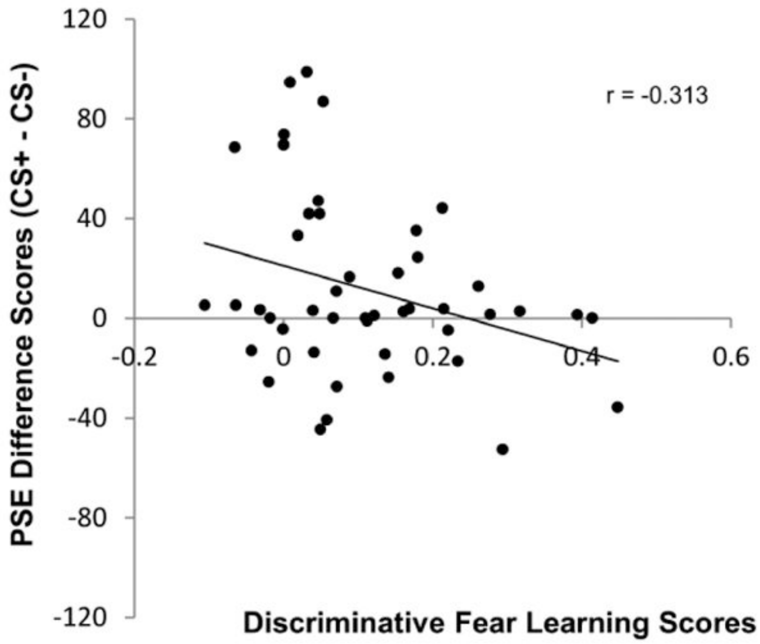

Figure 4.

Greater discriminative fear learning scores (difference in SCRs for CS+ > CS-) during conditioning predict less temporal underestimation on timing task trials coinciding with CS+ presentation (relative to CS- presentation).

Table 1

Means (SDs) for Subjective Ratings of Arousal and Valence of Stimulation

Stimulation Type	Conditioning		Timing Task	
	Arousal	***Valence***	***Arousal***	***Valence***
Aversive shock (US)	*5.09 (1.71)*	*4.44 (1.13)*	5.33 (2.07)	*3.96 (1.43)*
Non-aversive tactile	2.07 (1.06)	*5.63 (1.22)*	2.20 (1.50)	*5.65 (1.45)*

Table 2

Means (SDs) for Point of Subjective Equality (PSE) and Weber Fraction (WF) Scores

Cue Type	PSE	WF
CS+	407.80 (28.77)	0.051 (0.054)
CS-	396.27 (31.08)	0.043 (0.049)