Estimation of Time-to-Collision for Threat Stimuli

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Date: 2020-06-09T00:00:00+00:00

Abstract

The estimation of time-to-collision (TTC) for approaching motion stimuli is of significant evolutionary importance. To explain how individuals estimate TTC, researchers have proposed structuralist theory, ecological optics theory, and tau theory, among others, and have also investigated some factors that influence TTC estimation. Recent studies have examined the impact of stimulus emotion-related attributes on TTC estimation by comparing individuals' TTC estimates for threatening versus non-threatening stimuli. Results indicate that, compared to natural non-threat stimuli (e.g., images of rabbits), individuals underestimate the TTC of natural threat stimuli (e.g., images of snakes); however, this TTC underestimation is sometimes small or even non-significant for social threat stimuli (e.g., images of angry faces). Three potential reasons for TTC underestimation are: (1) individuals exhibit specific responses to threat stimuli; (2) threat stimuli possess higher emotional arousal; and (3) individuals have perceptual biases whereby threat stimuli are perceived as psychologically closer and moving faster. Future research could further investigate the causes of the unstable TTC underestimation effect observed with social threat stimuli; explore the autonomic physiological responses and neural mechanisms underlying TTC estimation of threat stimuli; adopt virtual reality technology in studies on TTC estimation of threat stimuli; and account for individual factors such as gender and personality traits in experimental design.

Full Text

Preamble

Estimating Time-to-Collision with Threatening Stimuli

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Abstract

Estimating the time-to-collision (TTC) with threatening stimuli holds important evolutionary significance. To explain how individuals estimate TTC, researchers have proposed theories such as the constructivist approaches, ecological optics theory, and tau hypothesis, and have also examined factors influencing TTC estimation. Recent studies have investigated how the emotional attributes of stimuli affect TTC estimation by comparing individuals' TTC estimates for threatening versus non-threatening stimuli. Results show that compared to natural non-threatening stimuli (e.g., rabbit images), individuals underestimate the TTC of natural threatening stimuli (e.g., snake images), but this TTC underestimation is sometimes small or even non-significant for social threatening stimuli (e.g., angry face images). Three possible reasons for TTC underestimation are: (1) individuals have a specific response to threatening stimuli; (2) threatening stimuli have higher emotional arousal; and (3) individuals have perceptual biases that threatening stimuli appear psychologically closer and move faster. Future research could further investigate the reasons for the unstable TTC underestimation effect observed with social threatening stimuli; explore the autonomic physiological responses and neural mechanisms underlying TTC estimation of threatening stimuli; conduct research on TTC estimation of threatening stimuli using virtual reality technology; and consider individual factors such as gender and personality traits in experimental designs.

Keywords

time-to-collision estimation; threat-specific response; arousal; psychological distance; speed perception

When driving a vehicle, drivers must accurately assess the movement of surrounding vehicles; when hitting a tennis ball flying toward them, athletes similarly need to precisely judge the ball' s trajectory. In these scenarios, whether to avoid contact with an object or to intentionally make contact, individuals must continuously estimate the time it would take for a collision between themselves and an approaching object (time-to-collision, TTC). Generally, individuals estimate the TTC of approaching objects primarily based on factors such as the distance between the stimulus and themselves, the object' s motion speed, the viewing angle, and the rate of change in viewing angle (陶维东, 陶晓丽, & 孙弘进, 2011)—that is, they rely mainly on the physical properties of the stimuli. However, in interacting with the environment, humans constantly face various threats, such as threatening animals in nature (spiders and snakes) (Basanovic, Dean, Riskind, & MacLeod, 2017; Hoehl & Pauen, 2017; Sagliano, Cappuccio, Trojan, & Conson, 2014), others displaying negative emotional expressions (angry and fearful faces) (Morris et al., 1996; Springer, Rosas, McGetrick, & Bowers, 2007), and certain threat cues in social contexts (vehicles and guns) (Han, Gao, Humphreys, & Ge, 2008). Previous research has found that to effectively respond to danger, individuals have developed adaptive representations of threatening stimuli. For example, they exhibit selective attention toward threats (Arnaudova, Krypotos, Effting, Kindt, & Beckers, 2017; Salemink, van den Hout, & Kindt, 2007); prepare defensive responses in advance (de Haan, Smit, Van der Stigchel, & Dijkerman, 2016); and possess a "fast fear pathway" in the nervous system (Das et al., 2005; LeDoux, 2000; Liddell et al., 2005). These threat-adaptive representations, shaped through long-term evolution, ensure individual survival. Would TTC estimation for approaching threatening stimuli also exhibit similar adaptive representations? The answer is yes.

In recent years, several studies have begun to examine individuals' TTC estimation for approaching threatening versus non-threatening stimuli. Results show that compared to non-threatening stimuli, participants perceive threatening stimuli as colliding with themselves earlier (Brendel, DeLucia, Hecht, Stacy, & Larsen, 2012; DeLucia, Brendel, Hecht, Stacy, & Larsen, 2014; Vagnoni, Andreanidou, Lourenco, & Longo, 2017; Vagnoni, Lourenco, & Longo, 2012, 2015)—that is, individuals underestimate the TTC of approaching threatening stimuli. This TTC underestimation effect for threatening stimuli provides individuals with sufficient preparation time to effectively respond to imminent danger, holding significant importance for survival and development.

Although existing research has identified the phenomenon of TTC underestimation for threatening stimuli, the specific mechanisms underlying this effect remain unclear. Based on recent studies investigating TTC estimation of approaching threatening stimuli, this article organizes two primary explanations for TTC underestimation: one suggests it stems from individuals' specific responses to threatening stimuli, while the other attributes it to the high arousal elicited by threatening stimuli. Additionally, perceptual biases in psychological distance and motion speed for threatening stimuli may also contribute to TTC underestimation. Finally, this article proposes directions for future research on TTC estimation of threatening stimuli.

2.1 TTC Estimation

TTC refers to the time required for an approaching object to collide with a stationary observer (DeLucia, Kaiser, Bush, Meyer, & Sweet, 2003; DeLucia & Liddell, 1998). TTC estimation represents an individual' s subjective judgment of this time interval, constituting a form of time perception. In experimental settings, researchers typically employ a TTC judgment task to assess individuals' TTC estimation for approaching stimuli. In this task, researchers present a stimulus image on a computer screen that gradually increases in size frame-by-frame to create an approaching motion effect. After approximately one second of motion, the stimulus disappears. Participants are then asked to imagine that the vanished stimulus continues its approach at the same speed and to press a button as quickly as possible at the moment they feel the stimulus would collide with them. The reaction time serves as the measure of TTC estimation (Brendel et al., 2012; Brendel, Hecht, DeLucia, & Gamer, 2014; DeLucia et al., 2014; Vagnoni, Andreanidou et al., 2017; Vagnoni, Lourenco et al., 2012, 2015).

2.2 Classic Theoretical Explanations of TTC Estimation

Among the classic theoretical explanations of TTC estimation, the most representative are the constructivist approaches, ecological optics theory, and the tau hypothesis. The constructivist approaches propose that individuals estimate TTC using two types of cues: changes in distance between the approaching object and themselves, and changes in object velocity (t=s/v) (Smeets, Brenner, Trebuchet, & Mestre, 1996; 陶维东 et al., 2011). Ecological optics theory suggests that visual stimuli are presented in our visual field as an optical array, and when stimuli move, the structure of this array changes (Kim, 2015). When an object approaches, individuals can directly estimate TTC based on changes in the optical array (McLeod & Ross, 1983). The tau hypothesis posits that humans and animals estimate TTC based on the derivative of tau (Hecht & Savelsbergh, 2004; Lee, 1976). This theory, developed from ecological optics theory, defines tau as the ratio between the viewing angle of the observed object and the rate of change in that angle. Subsequent research has revised the tau hypothesis, specifying the situational conditions to which it applies (Tresilian, 1997).

3 TTC Estimation for Threatening Stimuli

The commonality among these three theories is that they all construct theoretical models based on the physical properties of stimuli. However, in collision scenarios where an approaching stimulus threatens personal safety, individuals' TTC estimation for that stimulus may become biased. In recent years, several studies have examined the characteristics of TTC estimation for different types of threatening stimuli. This section briefly describes the effects of natural threatening stimuli (threatening animal images) and social threatening stimuli (angry face images) on TTC estimation (Brendel, 2019; Brendel, DeLucia et al., 2012; Brendel, Hecht et al., 2014; DeLucia et al., 2014; Vagnoni et al., 2012, 2015). In practice, some researchers in existing studies have not strictly distinguished between these two types of threatening stimuli, often using them interchangeably. To facilitate comparison across studies, the following discussion will treat them separately.

3.1 TTC Estimation for Natural Threatening Stimuli

In nature, many animals (e.g., snakes and spiders) pose threats to our personal safety (Lindner, Miloff, Reuterskiold, Andersson, & Carlbring, 2019). Brendel et al. (2012) used images of people, objects, mushrooms, and plants from the International Affective Pictures System (IAPS) as neutral stimuli, and images of snarling pit bulls, open-mouthed snakes, and masked kidnappers holding knives as threatening stimuli. By enlarging the stimulus images to create an approaching motion effect, they asked participants to complete a TTC judgment task. Results showed that participants' TTC estimates for threatening stimuli were significantly shorter than for neutral stimuli. Using a similar experimental paradigm, Vagnoni et al. (2012) employed spider and snake images as threatening stimuli and butterfly and rabbit images as non-threatening stimuli, requiring participants to perform a TTC judgment task. They found that participants' TTC estimates for threatening stimuli were significantly shorter than for non-threatening stimuli. Later, DeLucia et al. (2014) used a similar paradigm to examine TTC estimation for threatening scene images (snarling pit bulls, masked kidnappers with knives), neutral images (lamps, clocks), and friendly images (boys, babies). Again, results showed that participants' TTC estimates for threatening scene images were significantly shorter than for neutral and friendly images.

In a subsequent study, Vagnoni et al. (2015) again used spider and snake images as threatening stimuli and butterfly and rabbit images as non-threatening stimuli, recording participants' EEG activity via ERP technology while they performed TTC estimation. Their analysis of behavioral results still revealed TTC underestimation under threatening conditions. Meanwhile, analysis of ERP components showed that for different stimulus types, the amplitude changes of P1 in the occipital visual cortex and N1 in the prefrontal cortex were significantly smaller under threat versus non-threat conditions, while occipital N1 amplitude was significantly larger under threat conditions. For different approach speeds, parietal N1 amplitude increased with stimulus motion speed. Their analysis of EEG spectral activity during TTC estimation, based on time windows (three total: 500-1000 ms, 1000-1500 ms, and 1500-2000 ms from stimulus onset), stimulus type, and actual TTC conditions, revealed that compared to non-threatening conditions, threatening conditions showed stronger desynchronization in the α band (8-13 Hz), which weakened in the third time window. Analysis of the γ band (70-190 Hz) found that stimulus type and time window jointly affected neural activity in this frequency range, specifically showing stronger desynchronization under threatening conditions during the second time window.

In studies of early cognitive processing and emotional perception, P1 is generally considered an indicator of early attention allocation originating from the visual cortex (Baumgartner, Graulty, Hillyard, & Pitts, 2018; Fu, Caggiano, Greenwood, & Parasuraman, 2005; Smith, Cacioppo, Larsen, & Chartrand, 2003). Negative or threatening stimuli elicit greater P1 amplitude changes than positive or non-threatening stimuli (Carretie, Hinojosa, Martin-Loeches, Mercado, & Tapia, 2004; Delplanque, Lavoie, Hot, Silvert, & Sequeira, 2004; Venetacci, Johnstone, Kirkby, & Matthews, 2018). Therefore, differences in P1 amplitude between threatening and non-threatening stimuli during TTC estimation may indicate that the two stimulus types capture different attentional resources in early processing stages. This ability to rapidly differentiate between stimulus categories within the first 100 ms provides a mechanism for individuals to effectively respond to environmental threats. This also suggests that emotion' s role in information processing may be to concentrate cognitive resources to effectively guide behavioral responses, enabling individuals to appropriately react to important stimuli in the environment (Zajonc, 1980). Following P1, a negative ERP component called N1 emerges. In many contexts, N1 is considered sensitive to stimulus color (Anllo-Vento & Hillyard, 1996), location (Martinez, Teder-Salejarvi, & Hillyard, 2007; Martinez et al., 2006), and motion state (Lorteije, van Wezel, & van der Smagt, 2008). It is also closely related to the emotional properties of stimuli, with positive and negative emotional stimuli eliciting significantly greater N1 amplitude changes than neutral stimuli (Gupta, Kujawa, & Vago, 2019; Hart, Lucena, Cleary, Belger, & Donkers, 2012; Keil, Bradley et al., 2002; Keil, Muller et al., 2001). Thus, the phenomenon of significantly larger occipital N1 amplitude under threatening versus non-threatening conditions in TTC estimation may indicate that individuals' perception of stimulus motion state and distance changes differs from the early stages of processing when the two stimulus types are in motion, with threatening stimuli' motion states potentially receiving greater attention. Beyond individual ERP components reflecting neural activity in emotional information processing, some researchers believe that event-related analyses of synchronization and desynchronization across different EEG frequency bands can also reveal associations between emotional information processing and neural activity (Aftanas, Koshkarov, Pokrovskaja, Lotova, & Mordvintsev, 1996; Aftanas, Varlamov, Pavlov, Makhnev, & Reva, 2001; Krause, Viemero, Rosenqvist, Sillanmaki, & Astrom, 2000). Research indicates that desynchronization in the α band recorded from posterior electrodes occurs primarily during perceptual and later cognitive processing stages, relating to semantic information about stimuli (Aftanas et al., 2001) and influenced by the emotional meaning of stimuli (Krause et al., 2000). Therefore, stronger α desynchronization under threatening conditions during TTC estimation suggests that the emotional attributes of threatening stimuli continue to influence information processing from stimulus identification through disappearance, with this influence persisting for some time after stimulus offset. Furthermore, research shows that γ band activity relates not only to perceptual binding and multisensory integration (Quinn et al., 2014) but also to emotional information processing. Among different emotional stimulus types, negative emotional stimuli elicit the strongest γ band activity, and compared to positive emotional stimuli, negative stimuli produce stronger γ activity in the left temporal lobe (Keil et al., 2001; Muller, Keil, Gruber, & Elbert, 1999; Oya, Kawasaki, Howard, & Adolphs, 2002). Additionally, γ band activity is closely related to behavioral response preparation, such as preparing interceptive or defensive responses during object approach (Billington, Wilkie, Field, & Wann, 2011). Thus, stronger γ desynchronization under threatening conditions from the middle stage of TTC estimation until response preparation indicates that threatening stimuli more strongly elicit preparation for impending collision.

Integrating the above analyses of P1, N1, α band, and γ band, during TTC estimation for threatening versus non-threatening stimuli, threatening stimuli capture more attentional resources in early processing stages. After the two stimulus types are identified, the emotional attributes of threatening stimuli continue to influence ongoing information processing, with this influence persisting for some time after stimulus disappearance. Finally, before individuals make their response, threatening stimuli more strongly evoke preparation for the impending collision. This series of processes leads to TTC underestimation for threatening stimuli.

The aforementioned studies demonstrate from both behavioral and neural activity perspectives that individuals underestimate the TTC of approaching natural threatening stimuli. This indicates that when stimuli approach an individual, their emotion-related attributes can bias subjective time perception, causing individuals to judge that a collision will occur earlier.

3.2 TTC Estimation for Social Threatening Stimuli

Beyond animals in nature that may threaten our personal safety, there are also threat factors within our social groups, such as enemies and assailants. Different emotional states in humans can be expressed through facial expressions, which allow us to accurately judge whether others harbor hostility toward us. Angry expressions convey information about an individual being provoked and potentially engaging in aggressive behavior. Consequently, many studies treat angry facial expressions as a form of social threatening stimulus (Brendel et al., 2012; DeLucia et al., 2014). Such social threatening stimuli may similarly influence TTC estimation. In Experiment 3, Brendel et al. (2012) used angry, happy, and neutral facial expressions as stimuli and required participants to complete a TTC judgment task. Results showed that participants' reaction times for TTC estimation of angry faces were significantly shorter than for the other two expression types, indicating that social threatening stimuli represented by angry faces also lead to TTC underestimation. However, in DeLucia et al.' s (2014) research, Experiment 1 used angry, happy, and neutral faces of two male models from the NimStim face database as stimulus materials, while Experiment 2 used threatening, neutral, and friendly scene images from the IAPS. Both experiments required participants to complete TTC judgment tasks. Results showed TTC underestimation for threatening emotional scene images in Experiment 2, but no TTC underestimation for angry face images in Experiment 1.

Thus, findings from these two studies present inconsistent results regarding TTC estimation for social threatening stimuli.

This inconsistency may partly arise from differences in face presentation duration. Comparing the two studies, they used identical face materials (both from two male models in the NimStim database, numbers 20 and 23), but with different presentation times. In Brendel et al. (2012), face presentation duration was 200 ms and 800 ms, whereas in DeLucia et al. (2014), it was 3000 ms. Numerous ERP studies have found that face stimuli elicit a negative ERP component in the occipital visual cortex within a 100-200 ms time window, peaking around 170 ms—known as the N170 component, considered face perception-specific (Bentin, Allison, Puce, Perez, & McCarthy, 1996; Rossion, 2014; Rossion et al., 2000). Additionally, a magnetoencephalography (MEG) study investigating the role of face presentation time in face perception found that brain magnetic activity elicited by faces was strongest at 200 ms presentation duration (Tanskanen, Nasanen, Ojanpaa, & Hari, 2007). These findings suggest that human brain processing of faces can be completed within a short time. Under longer presentation durations, participants' attention to emotional information in faces may diminish, potentially shifting focus to other facial attributes such as gender, identity, and skin texture (Fisher, Towler, & Eimer, 2016; Schweinberger & Soukup, 1998). Moreover, under longer presentation durations, participants' emotional experience of faces may be modulated by later cognitive appraisal, thereby reducing the TTC underestimation effect.

This inconsistency may also stem from arousal differences due to different presentation methods for the same faces. In Brendel et al. (2012), faces were presented via a stereoscopic large screen (78-degree diagonal viewing angle), whereas in DeLucia et al. (2014), faces were presented on a non-stereoscopic small screen (50-degree diagonal viewing angle), creating size differences in how faces were displayed. Research has shown that the size of presented faces affects emotional arousal, with larger faces rated as significantly more arousing than smaller faces (Codispoti & de Cesarei, 2007). Therefore, differences in emotional arousal between the two presentation methods may have caused variations in participants' TTC estimation for identical materials. The specific mechanism through which arousal influences TTC estimation will be discussed in Section 4.2.

4 Reasons for Underestimating TTC of Threatening Stimuli

Existing research demonstrates that individuals underestimate the TTC of threatening stimuli. The ensuing question is: What causes this effect? This section discusses potential reasons for TTC underestimation of threatening stimuli from three perspectives: individuals' specific responses to threatening stimuli, the high arousal of threatening stimuli, and perceptual biases in psychological distance and motion speed for threatening stimuli.

4.1 Specific Responses to Threatening Stimuli

Through long-term evolution, organisms have developed specific responses to threatening stimuli. Numerous studies have found that threatening stimuli possess perceptual salience (Balaban & Taussig, 1994); individuals show selective attentional bias toward threatening stimuli (Sagliano, Trojano, Amoriello, Migliozzi, & D' Olimpio, 2014; Salemink et al., 2007); individuals can effectively detect threatening stimuli even without conscious awareness (Ohman & Soares, 1993); and primate nervous systems contain neurons specifically sensitive to threatening stimuli (Van Le et al., 2013). Therefore, from an evolutionary perspective, TTC underestimation may originate from individuals' specific responses to threatening stimuli, or alternatively, TTC underestimation may itself constitute a manifestation of these specific threat responses. Indeed, Vagnoni et al. (2012) also explained TTC underestimation for threatening stimuli from an evolutionary standpoint, arguing that underestimating TTC provides more time for the fight-or-flight decision when facing threats. Additionally, this evolutionary explanation can account for why TTC is more easily underestimated for natural threatening stimuli. Throughout evolutionary history, individuals encountered natural threats (e.g., snakes and spiders) much earlier than social threats (e.g., masked assailants with knives). Consequently, natural threatening stimuli carry greater evolutionary significance, resulting in more profound effects on TTC estimation.

4.2 High Arousal of Threatening Stimuli

From the perspective of stimulus emotional attributes, threatening stimuli have both lower valence and higher arousal compared to neutral stimuli. Therefore, TTC underestimation may also relate to the higher arousal elicited by threatening stimuli. Brendel et al. (2014) investigated the influence of stimulus arousal on TTC estimation. They continued using threatening stimuli from previous research while selecting erotic and monetary images from the IAPS as non-threatening stimuli matched for equivalent arousal levels. Participants completed the same TTC judgment task. Results showed that participants exhibited TTC underestimation for both threatening and non-threatening stimuli, with even shorter TTC estimates for non-threatening stimuli. This study suggests that TTC underestimation for threatening stimuli may be related to the high arousal of the stimuli themselves.

Furthermore, as mentioned earlier, TTC underestimation effects are relatively stable when using natural threatening stimuli (threatening animal images) but less stable when using social threatening stimuli (angry faces) (Brendel et al., 2012; DeLucia et al., 2014), which may also relate to differences in emotional arousal between social and natural threatening stimuli (DeLucia et al., 2014). Wangelin, Bradley, Kastner, and Lang (2012) compared skin conductance level (SCL) and late-positive potential (LPP) elicited by facial emotion images (angry, neutral, and happy) and natural emotion images (negative, neutral, and positive). SCL, an indicator of skin conductivity changes following emotional stimulation, is closely related to emotional arousal and increases with arousal level (易欣, 葛列众, & 刘宏艳, 2015; Bradley, Codispoti, Cuthbert, & Lang, 2001; Codispoti et al., 2007; Codispoti, Surcinelli, & Baldaro, 2008). The LPP component also has a close relationship with emotional arousal (Herbert, Sfarlea, & Blumenthal, 2013), showing larger amplitude changes for high-arousal emotional stimuli compared to low-arousal neutral stimuli (Olofsson, Nordin, Sequeira, & Polich, 2008). Wangelin et al. (2012) found that compared to angry face conditions, participants showed shorter reaction times to probe stimuli, higher SCL, and larger LPP amplitude changes under natural negative image conditions, indicating that natural negative images have higher emotional arousal than angry faces.

Additionally, research using negative emotional images with different arousal levels has examined arousal' s role in time perception. Researchers selected high- and low-arousal disgust and sadness images, high-arousal disgust and fear images, and matched neutral images from the IAPS. Images were presented for varying durations, and participants were asked to input the presentation duration in milliseconds after image offset. Results showed that participants estimated longer presentation durations for disgust, sadness, and fear images compared to neutral images, and this subjective time perception lengthening effect increased with the arousal level of the three emotional image categories (Gil & Droit-Volet, 2012). This phenomenon of emotional arousal lengthening subjective time perception can be explained by the scalar expectancy theory of time perception, which posits that time judgment involves three stages: clock, memory, and decision (Gibbon, Church, & Meck, 1984; Lake, LaBar, & Meck, 2016; Lehockey, Winters, Nicoletta, Zurlinden, & Everhart, 2018). In the clock stage, a pacemaker emits pulses that are collected by an accumulator, with the number of collected pulses representing time duration.

Researchers propose that arousal influences time perception by increasing the pacemaker' s pulse emission frequency, thereby accelerating the organism' s internal clock (Cheng, Tipples, Narayanan, & Meck, 2016; Droit-Volet, 2013; Fayolle, Gil, & Droit-Volet, 2015; Lake, Meck, & LaBar, 2016), causing the accumulator to collect more pulses. This explanation of arousal increasing pacemaker frequency also applies to TTC underestimation for threatening stimuli. Similarly, TTC estimation involves a clock stage—from stimulus disappearance until participants feel the stimulus would collide with them. The number of pulses accumulated during this stage represents the TTC estimate. Compared to non-threatening or low-arousal stimuli, when threatening stimuli appear, their higher arousal increases pacemaker pulse frequency, accelerating the internal clock. This influence persists after stimulus disappearance, increasing pulse accumulation during the TTC estimation clock stage and causing individuals to complete TTC estimation earlier.

Furthermore, arousal' s influence on time estimation may relate to changes in internal hormone levels. Research has found that high-arousal stimuli can cause changes in the peripheral nervous system and hormone levels (Hasselmo & Sarter, 2011; Lang & Bradley, 2010; LeDoux, 2000; Pessoa & McMenamin, 2017). Studies have examined hormone level changes in time perception. Soares, Atallah, and Paton (2016) used optogenetic techniques to measure dopaminergic neuron activity in mice during interval timing estimation, subsequently manipulating dopamine release by expressing excitatory and inhibitory optogenetic proteins in dopaminergic neurons. They found that inhibiting dopaminergic neurons reduced mice' s time sensitivity and that briefly activating or inhibiting dopaminergic neuron activity could effectively manipulate mice to underestimate or overestimate stimulus intervals. Another study used pharmacological inhibition, locally injecting nomifensine—a norepinephrine and dopamine reuptake inhibitor—into the prelimbic cortex. Results showed that nomifensine effectively reduced anxiety-inducing stimuli' s impairing effects on time estimation compared to neutral stimuli (Matthews, He, Buhusi, & Buhusi, 2012). These findings suggest that stimuli with different emotional arousal levels influence time perception by altering internal hormone levels.

Although the above research demonstrates arousal' s important role in TTC underestimation for threatening stimuli, it is not the sole influencing factor and cannot explain all experimental results. Indeed, Vagnoni et al. (2012) reported a control experiment using an emotional priming paradigm. In the experiment, participants first viewed threatening or non-threatening stimuli for 1 second, followed by an approaching blue disk, and were asked to complete a TTC judgment task for the blue disk. The hypothesis was that if stimulus arousal caused TTC underestimation, participants would still underestimate the blue disk' s TTC after threatening stimulus priming. However, no significant difference in TTC estimation for the blue disk existed between the two priming conditions, suggesting that TTC underestimation for threatening stimuli is not caused by arousal but rather by the threatening nature of the stimuli themselves. However, this experiment used a priming paradigm where the stimulus seen before the blue disk was relatively small, and stimulus arousal positively correlates with stimulus size (Codispoti et al., 2007). Therefore, arousal elicited by the initial stimulus was not high. Additionally, after image disappearance, participants imagined the blue disk' s approach rather than the threatening or non-threatening stimulus' s approach, so emotional arousal may have dissipated quickly over time. Thus, these results may be indirect. In contrast, Experiment 3 in Brendel et al. (2014) more directly investigated the roles of arousal and valence in TTC estimation. They selected IAPS images as stimuli, systematically manipulating arousal and valence. Arousal had four levels: very low, low, medium, and high; valence had three levels: low, medium, and high. Neutral stimuli with very low arousal and medium valence were also included, along with solid color images as filler stimuli. These stimuli included those used in their 2012 study.

The task remained a TTC judgment task. Results showed a significant interaction between arousal and valence. Specifically, participants had the shortest TTC estimates for medium-arousal high-valence stimuli, followed by high-arousal low-valence stimuli. TTC estimates for medium- and high-arousal low-valence stimuli and medium-arousal high-valence stimuli did not differ significantly from solid color stimuli. Participants had the longest TTC estimates for neutral stimuli (low arousal, medium valence). This suggests that TTC underestimation for approaching threatening stimuli may result from the combined effects of stimulus arousal and valence.

4.3 Perceptual Biases in Psychological Distance and Motion Speed for Threatening Stimuli

Additionally, perceptual biases in psychological distance and motion speed for threatening stimuli may indirectly influence TTC estimation. Research has examined individuals' psychological distance from threatening objects in the environment. In one experiment, researchers placed a live tarantula on a table at a certain distance from participants, who first estimated the spider' s distance from themselves and then rated whether they felt threatened or disgusted. Results showed that participants who felt threatened estimated the spider as closer than those who felt disgusted (Cole, Balcetis, & Dunning, 2013). Harber, Yeung, and Iacovelli (2011) reported similar findings. Furthermore, our perceived distance from other groups is influenced by those groups' social threat level. Xiao and Van Bavel (2012) conducted three experiments examining individuals' distance perception to locations of outgroups. In Experiment 1, New York Yankees fans and non-fans at Yankee Stadium estimated distances from Yankee Stadium to Fenway Park (threatening outgroup location) and Camden Park (neutral outgroup location). In Experiment 2, New York University (NYU) members and non-members estimated distances from NYU to Columbia University (potentially threatening, with higher comprehensive ranking) and Hunter College (non-threatening, with lower ranking). In Experiment 3, NYU undergraduates first read positive descriptions of American people and negative descriptions of Mexican immigrants, then estimated distances from New York to Mexico and to Vancouver (similar distance to Mexico). Results across all three experiments showed that participants estimated threatening outgroup locations as closer to themselves. These findings demonstrate that when a perceptual object is threatening, individuals perceive its spatial distance as significantly shortened.

Our motion speed perception for threatening stimuli also shows biases. Riskind, Kelley, Harman, Moore, and Gaines (1992) proposed the harm-looming model, suggesting that anxious individuals perceive threatening stimuli as moving faster and are more likely to perceive their motion direction as approaching themselves. In a later study, Riskind, Moore, and Bowley (1995) examined individuals' motion perception of spider images in imagined scenarios, finding that individuals with spider phobia perceived poisonous spiders as moving toward them faster than non-phobic individuals. Additionally, a recent study investigated differences in speed perception of spiders and butterflies among individuals with varying levels of spider fear. High and low spider-fear groups judged which of paired spider and butterfly images moved fastest under approaching and receding motion conditions. Results showed that under approaching motion conditions, high spider-fear individuals were more likely than low-fear individuals to perceive spiders as moving fastest (Basanovic, Dean, Riskind, & MacLeod, 2019). These findings indicate that when individuals perceive moving stimuli as threatening, they overestimate the stimuli' s relative motion speed.

Therefore, during TTC estimation, individuals may perceive the spatial distance between themselves and threatening stimuli as significantly shorter than the actual distance, while simultaneously perceiving threatening stimuli' s motion speed as significantly faster than actual speed. According to the familiar physics formula where time equals distance divided by speed, either a decrease in the numerator (distance) or an increase in the denominator (speed)—or both—can lead to TTC underestimation. If so, the constructivist approaches, despite not originally considering emotional factors, could precisely explain the phenomenon of TTC underestimation for threatening stimuli. Future researchers could conduct empirical studies on this topic.

5 Summary and Outlook

This article has organized the concept of TTC, experimental tasks for TTC estimation, and classic explanatory theories, reviewing recent research on individuals' TTC estimation for threatening stimuli. We analyzed reasons for underestimating TTC for approaching threatening stimuli from three perspectives: individuals' specific responses to threatening stimuli, high arousal of threatening stimuli, and perceptual biases in psychological distance and motion speed for threatening stimuli. However, many unresolved issues remain in current research on TTC estimation for approaching threatening stimuli that require future investigation.

First, further explore the reasons for the unstable TTC underestimation effect with social threatening stimuli. As discussed earlier, threatening animal images and threatening face images produce different effects on TTC estimation, possibly because they activate different cognitive processing systems (DeLucia et al., 2014; Ohman, 1986). Threatening animal images more strongly activate the innate defense system, which has evolved over the long term and operates with strong automaticity. In contrast, threatening face images more strongly activate individuals' social defense system, which is regulated by cognitive appraisal and operates with weaker automaticity than the innate defense system. Additionally, Han et al. (2008) found a brain network for threat detection and evaluation that is independent of fear emotion. Therefore, the mechanisms underlying TTC underestimation effects for threatening stimuli may be complex.

Second, investigate the role of arousal in TTC underestimation for threatening stimuli by incorporating autonomic physiological response indicators such as SCL. As previously discussed, emotional arousal may be one cause of TTC underestimation, and SCL is closely related to stimulus emotional arousal (易欣 et al., 2015). During TTC estimation, SCL under threatening conditions may be significantly higher than under non-threatening conditions, reflecting a state of higher self-activation. Including physiological indicators like SCL can provide more direct evidence for exploring the role of this potential factor.

Third, examine activation patterns in regions such as the primary visual cortex, sensorimotor cortex, thalamus, and amygdala, as well as functional connectivity between these regions, during TTC estimation for approaching threatening stimuli. Single-cell recording studies have found specialized neurons in crabs (Oliva, Medan, & Tomsic, 2007), locusts (Gray, Blincow, & Robertson, 2010), and pigeons (Xiao & Frost, 2009) that respond to visual information relevant to TTC estimation. fMRI research has also identified specific human brain regions related to TTC estimation for general stimuli, such as the V5/MT-MST area (Morrone et al., 2000; Smith, Wall, Williams, & Singh, 2006), sensorimotor cortex (Field & Wann, 2005), thalamus, and insula (Billington et al., 2011). However, previous research on TTC estimation for threatening stimuli has largely remained at the behavioral level, with neural activity and brain substrates yet to be explored. Future studies should combine specific neuronal activity with activity in these relevant brain regions to further reveal the neural mechanisms underlying TTC estimation for approaching threatening stimuli.

Fourth, use virtual reality (VR) technology to study TTC estimation for threatening stimuli. Previous research has primarily simulated approaching motion by enlarging stimulus images on flat displays, which does not equivalently represent real situations. This limits generalization of laboratory findings to real-world contexts. In contrast, VR technology creates experimental environments with stronger three-dimensionality, more realistic distance and depth changes, richer interactions, and higher participant engagement (Rolin, Fooken, Spering, & Pai, 2019; Scarfe & Glennerster, 2015). Moreover, VR environments are suitable for studying psychological distance and motion speed perception related to depth. Therefore, future research should employ VR technology to further investigate characteristics of TTC estimation for threatening stimuli in relatively realistic environments, yielding conclusions with higher ecological validity.

Fifth, examine individual factors in TTC estimation for threatening stimuli. Previous research has shown gender differences in emotional experience of emotional images and identification of emotion types in facial expression images. For example, women are more sensitive to negative emotional information in images and have stronger emotional experiences (Bianchin & Angrilli, 2012; Brebner, 2003; Fischer, Mosquera, van Vianen, & Manstead, 2004; Rakison, 2009). Additionally, in identifying emotion types from facial expression images, women show higher accuracy for negative emotions, while men show higher accuracy for positive emotions (Connolly, Lefevre, Young, & Lewis, 2019). Therefore, women may underestimate TTC for threatening stimuli more than men. Similarly, individuals with different personality traits, such as varying emotional sensitivity, may also show differences in TTC estimation for threatening stimuli. While previous research has focused more on external stimulus factors affecting TTC estimation for threatening stimuli, investigating internal individual factors such as gender and personality traits will help comprehensively reveal the underlying mechanisms of TTC estimation for threatening stimuli.

Estimating the time-to-collision with a threatening object

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Abstract: Estimating the time-to-collision (TTC) of approaching objects is crucial for organism survival. Researchers have proposed the constructivist approaches, the ecological optics theory and the tau hypothesis to explain how humans estimate TTC and which factors may affect the estimation. Recently, a few studies examined how the emotional content of stimuli impacts TTC estimation, by comparing TTC judgements between threatening and non-threatening stimuli. Their findings suggest that natural threatening stimuli (e.g., images of snakes) lead to underestimation of TTC compared to natural non-threatening stimuli (e.g., images of rabbits). However, other findings suggest that TTC underestimation of social threatening stimuli (e.g. pictures of angry faces) is smaller or absent. Underestimated TTC of threatening stimuli may be due to 1) a specific response to threatening stimuli, 2) high emotional arousal of threatening stimuli, and 3) a perceptual bias causing threatening stimuli to appear closer and move faster than typical. We suggest that future studies should (1) further investigate the reasons why TTC underestimation of social threatening stimuli is smaller or absent, (2) explore the autonomic physiological response patterns and neural correlates of TTC estimation of threatening stimuli, (3) examine TTC estimation of threatening stimuli in virtual reality (VR) environments, and (4) experimentally test the effects of individual differences (e.g., gender and personality traits) on TTC estimation.

Keywords: time-to-collision estimation; threat-specific response; emotional arousal; psychological distance; speed perception

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