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Differential contribution of velocity and distance to time estimation during self-initiated time-to-collision judgment

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ABSTRACT

To successfully intercept/avoid a moving object, human brain needs to precisely estimate the time-to-collision (TTC) of the object. In real life, time estimation is determined conjointly by the velocity and the distance of a moving object. However, surprisingly little is known concerning whether and how the velocity and the distance dimensions contribute differentially to time estimation. In this fMRI study, we demonstrated that variations of velocity evoked substantially different behavioral and neural responses than distance during self-initiated TTC judgments. Behaviorally, the velocity dimension induced a stronger time dilation effect than the distance dimension that participants' responses were significantly more delayed by increasing velocity than by decreasing distance, even with the theoretical TTC being equated between the two conditions. Neurally, activity in the dorsal fronto-parietal TTC network was parametrically modulated by variations in TTC irrespective of whether the variations in TTC were caused by velocity or distance. Importantly, even with spatial distance being equated, increasing velocity induced illusory perception of longer spatial trajectory in early visual cortex. Moreover, as velocity increased, the early visual cortex showed enhanced connectivity with the TTC network. Our results thus implied that with increasing velocity, TTC judgments depended increasingly on the velocity-induced illusory distance information from early visual cortex and was eventually tampered.

1. Introduction

Temporal prediction is one of the most important cognitive functions for daily survival (Coulle et al., 2011; Coull and Nobre, 2008). In order to successfully intercept or avoid a moving object, the human brain needs to precisely estimate the time-to-collision (TTC) of the object by implicitly extracting the temporal information inherent in its spatiotemporal trajectory, which implicates the sensorimotor cortex, the inferior parietal cortex, and the cerebellum (Assmus et al., 2005, 2003; Bares et al., 2007, 2010; Beudel et al., 2009; Bosco et al., 2008; Coull et al., 2008; Field and Wann, 2005; O'Reilly et al., 2008). In real life, timing is determined conjointly by the velocity and the distance of a moving object. However, surprisingly little is known with regard to whether and how the velocity and the distance dimensions contribute differentially to temporal prediction. For example, a fast yet far-away car may evoke substantially different behavioral and neuronal responses compared to a slow yet close car, even with the TTC being equated between the former and the latter cases.

In the present study, we aimed to investigate the potentially different contributions of the velocity and the distance dimensions to temporal prediction at both the behavioral and the neural levels. In a self-initiated TTC task, participants were asked to initiate the vertical movement of a dot, in order to hit a horizontally moving dot as precisely as possible (Fig. 1a). Two critical experimental conditions were introduced. In the velocity-increasing (distance-constant) condition, the distance of the horizontally moving dot remained constant, and the velocity parametrically increased across four levels so that the theoretical TTC parametrically decreased (Fig. 1b left). In the distance-decreasing (velocity-constant) condition, the velocity remained constant, and the distance parametrically decreased across four levels, resulting in four levels of parametrically decreasing TTC as well (Fig. 1b right). Most importantly, the slope of the four levels of TTC was identical between the two experimental conditions. To further control for the effects induced by differences in the physical features of stimuli, we asked participants to perform a control task (luminance judgment) on the same stimulus set as that in the TTC task.

Previous psychophysical experiments have documented that a faster moving object introduces longer subjectively experienced temporal duration than a slower object, which is termed as the velocity-induced time dilation effect (Brown, 1995; Kanai et al., 2006; Kaneko and Murakami, 2009; Makin et al., 2012). On the

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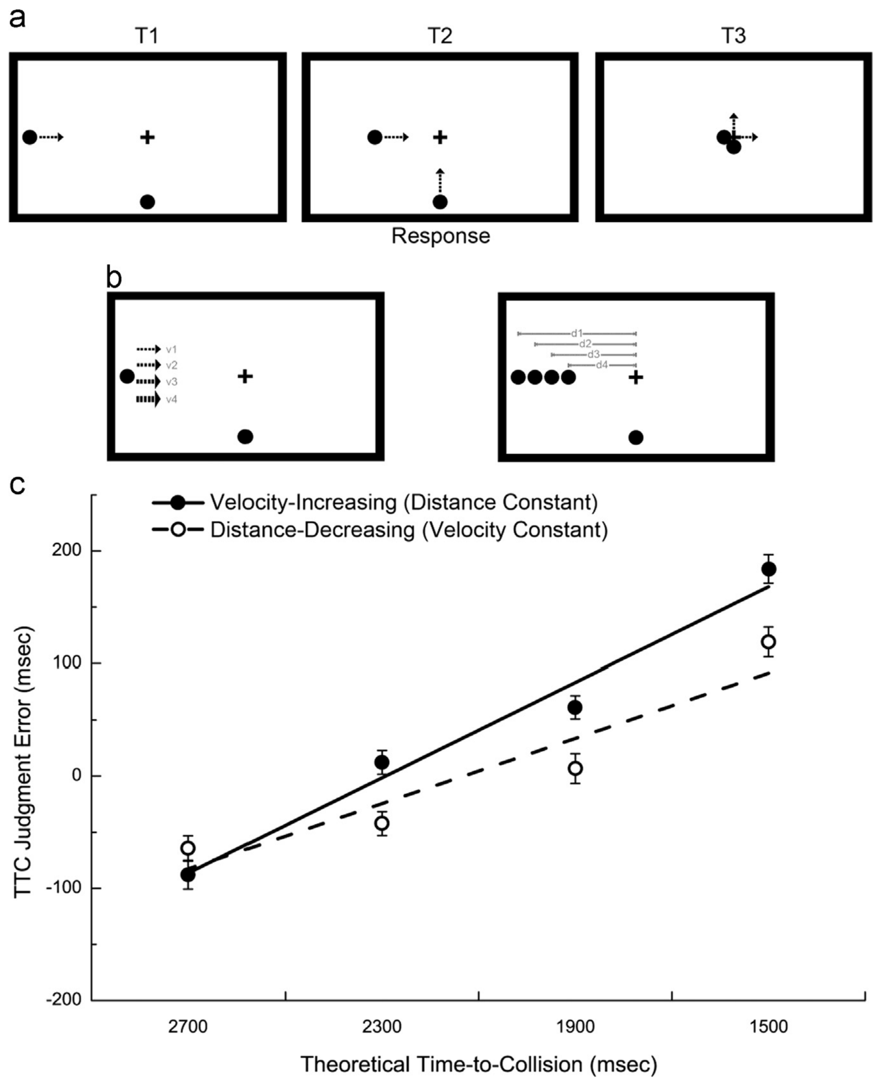

Fig. 1. Experimental stimuli, design, and behavioral results. (a) Experimental paradigm. In the self-initiated time-to-collision (TTC) task, each trial started with one horizontally moving dot and another stationary dot at a vertical peripheral position (T1). Participants were instructed to press a button to initiate the vertical movement of the stationary dot (T2) so that the two dots could collide as precisely as possible with each other (T3). (b) Experimental design. In the velocity-increasing (distance-constant) condition (left), the distance of the horizontally moving dot was constant and its velocity was parametrically increased across four levels so that the theoretical TTC was parametrically decreased. In the distance-decreasing (velocity-constant) condition (right), the distance was parametrically decreased across four levels and its velocity was kept constant, resulting in four levels of parametrically decreasing TTC as well. The four levels of the theoretical TTC were identical between the two experimental conditions. (c) Behavioral results. TTC error was calculated by subtracting the theoretical TTC, at which the two dots perfectly collided, from the actual time, at which the participants pressed the button. A negative TTC error thus indicated that participants responded ahead of the theoretical time while a positive TTC error indicated a delay in responses.

other hand, there was also evidence for the dependence of temporal judgments on the spatial distance (Cohen et al., 1953; Jones and Huang, 1982). In the present study, we examined the potentially differential effect of the velocity and the distance dimensions on temporal prediction. We predicted that, even with the theoretical TTC being equated, subjective estimation of TTC would be differentially modulated by variability of velocity and distance. At the neural level, we were most interested in dissociating the common and specific neural networks evoked by the parametrically varying velocity and distance during TTC judgments, respectively.

2. Materials and methods

2.1. Participants

Twenty adults (10 females, 23.6 ± 2.1 years old) participated in the present experiment. All participants were right-handed and had normal or corrected-to-normal vision. None of them had any history of neurological or psychiatric disorders. Informed consent was obtained from all participants prior to the experiment. The study was approved by the Ethics Committee of Department of Psychology, South China Normal University, and was conducted in accordance with the Declaration of Helsinki.

2.2. Stimuli and experimental design

Stimuli were presented using Presentation (Neurobehavioral Systems, http://www.neurobs.com). Stimuli were presented through a LCD projector onto a rear screen located behind the participant's head. Participants viewed the screen via an angled mirror mounted on the head-coil of the MRI setup. The default display consisted of a rectangle with black outlines (15.6° × 6.6° of visual angle) and a central fixation cross on a white background. Participants were instructed to fixate at the central cross throughout the experiment without moving their eyes. At the beginning of each trial, two black dots (0.4° of visual angle in