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Is judging time-to-contact based on 'tau'?

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Abstract. An investigation was undertaken into whether judgments of time-to-contact between a laterally moving object and a bar are based on the direct perception of an optical variable (tau), or on the ratio between the perceived distance and perceived velocity of the object. A moving background was used to induce changes in the perceived velocities without changing the optical variables that specify time-to-contact. Background motion induced large systematic errors in the estimated time-to-contact. It is concluded that the judgment of time-to-contact is primarily based on the ratio between the perceived distance and the perceived velocity, and not on tau.

1 Introduction

Knowing the time-to-contact with an object is important for hitting or catching it. Lee (1976) hypothesised that we gear our actions to the velocity of an object relative to ourselves, neglecting accelerations. If we do so, we do not need to use the perceived distance and perceived velocity to estimate the time-to-contact with the object. The inverse of the relative rate of expansion of the retinal image of the object, called 'τ' (tau), specifies the time-to-contact directly. Evidence that subjects use this variable to control interceptive actions originates from two kinds of experiments. Lee et al (1983) have shown that if the object is accelerating (resulting in a continuously changing value of τ), subjects gear their action to the value of τ rather than to the actual time-to-contact. Thus, subjects discard information on acceleration. Savelsbergh et al (1991) used deflating balls to show that the timing of catching depends on the rate of expansion of the retinal image of the ball. This finding is consistent with the proposed use of the relative rate of expansion for judging time-to-contact. The experiments of Heuer (1993), however, show that binocular information can change judgments of time-to-contact, which is not consistent with the predictions of the τ hypothesis.

In general, we do not only interact with objects that are moving directly towards our eyes. Moreover, we are seldom really interested in when objects will hit our eyes. The time-to-contact is therefore seldom specified by the relative rate of expansion of the object. Recently, Tresilian (1990) has derived several general expressions which give the time-to-contact between an object (moving at a constant velocity) and any chosen position in space. According to him, the most likely timing variable is calculated from three optical variables: the angular distance between the object and the position of interest, the angular velocity of the object, and the local τ. Recent experiments by Tresilian (1994) show that the angular position is indeed used for timing interceptive actions. For the same problem, Bootsma and Oudejans (1993) suggested a generalisation of τ. Their generalisation is not based on the rate of expansion of the object, but on the rate of constriction of a visual gap. They provide some evidence that the time-to-contact between two objects could be based on such a τ-like variable. In all these studies it is assumed that time-to-contact is judged directly from optical variables.

Using a different experimental paradigm, we showed that the timing of an interceptive action depends strongly on the perceived velocity of the target (Brenner and Smeets 1994a, 1994b; Smeets and Brenner 1995). The experiment (as some of Tresilian 1994) differed from the study of Bootsma and Oudejans (1993) in that the target (a moving spider) was not to be hit at a visually defined position. In that case, one cannot define a visual gap to describe the timing of the action. The experiment showed that timing of the arm movements was nevertheless based on visual information: it depended on the spider's speed. An important aspect of the experiment was that a distinction could be made between perceived velocity and (changes in) position. This was accomplished by using a moving background to change the perceived velocity of the object without changing its actual velocity or perceived position. To hit the moving spider, subjects geared their actions to the spider's apparent velocity rather than to its actual velocity.

This result has led us to formulate an alternative hypothesis for the information on which judgments of time-to-contact are based. We hypothesise that the perceived time-to-contact is the ratio of the perceived distance and perceived velocity. This hypothesis differs from Lee's (1976) original hypothesis [and the generalisations by Tresilian (1990) and Bootsma and Oudejans (1993)] in only one aspect. According to the τ hypothesis, time-to-contact is judged on the basis of optical variables (such as angular velocity or the rate of expansion), which specify directly the time-to-contact. In our hypothesis, however, it is assumed that time-to-contact is judged indirectly, on the basis of two distinct perceptual variables, perceived distance and perceived velocity.

The difference between the two hypotheses is more than pure semantics. The τ hypothesis has some clear theoretical advantages to our alternative. As mentioned by Bootsma and Oudejans (1993), the variable τ can be calculated by using only the angular distance ϕ between two objects: $1/\tau = \mathrm{d}/\mathrm{d}t \ln\phi$. This formulation stresses that the directly perceived variable τ does not require any transformation from angular to spatial coordinates, and is therefore very robust. Our alternative, on the other hand, is based on two transformed variables. As a result, any error in perceived distance or velocity will change the judgment of time-to-contact. This predicted sensitivity of time-to-contact for misjudgments is the property we will use to test our alternative against the τ hypothesis. The latter predicts a robust judgment.

In order to examine whether subjects use the relative rate of constriction of an optical gap when such a gap is present, we devised an experiment based on the design of Bootsma and Oudejans (1993). Subjects were asked to judge the time-to-contact between laterally moving objects and a bar. In this geometry, Tresilian's (1990) scheme becomes independent of local τ, and reduces to the ratio between (angular) distance and (angular) velocity. As the schemes of both Tresilian (1990) and Bootsma and Oudejans (1993) predict the same result for our experiment, we will refer to them both as the 'τ hypothesis'. We examined whether subjects judge time-to-contact directly on the basis of optical variables (τ hypothesis), or indirectly from the perceived velocity of the object and its perceived distance from the bar. Using the moving-background paradigm, we show that for laterally moving objects, time-to-contact judgments are mainly based on the ratio between perceived distance and perceived velocity.

2 Methods

2.1 *Subjects*

Twelve subjects (three of the authors, a visiting scientist, and eight colleagues from the Erasmus University) volunteered to take part in the experiment. Except for the authors, the subjects were naive with respect to the exact purpose in the experiment.

2.2 *Apparatus*

The stimuli were presented on a computer monitor (Silicon Graphics GTX-210 computer and HL69SG monitor). The monitor (34 cm× 27 cm, 1280 pixels × 492 pixels, frame rate 120 Hz) was viewed with the head on a chin rest at 38 cm distance (figure 1). The image on the screen was red, except for two windows (12 cm ×6 cm, separated by a bar of 0.2 cm), through which one could see a blue background with about 80 randomly oriented yellow lines (length 2 cm). This background was either stationary or moved at 1.5 cm s^{-1} to the right. Within each window a 1 cm×1 cm white square moved towards the centre of the screen. The square in the left window (constant) always made the same movement; it started 10.5 cm to the left of the bar, and moved for 1.3 s to the right, disappearing 4 cm from the bar. The movement of the right square (adjustable) was influenced by the subject; by using the computer mouse, either the final distance or the velocity of the right square could be manipulated. A sentence above the windows instructed the subject to match one aspect of the motion of the adjustable square to that of the constant one.

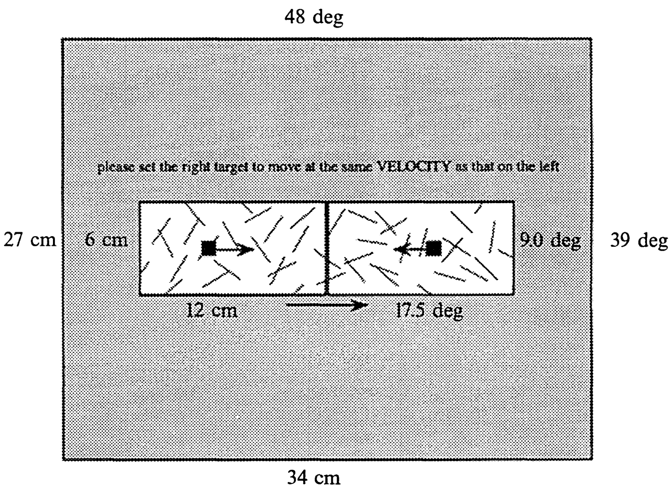

Figure 1. The display used in the experiment. Two squares and a background of randomly oriented lines are visible through two windows, separated by a bar. The left (constant) square always moved in exactly the same manner. The movement of the right (adjustable) square always moved in exactly the same manner. The movement of the right (adjustable) square could be manipulated by the subject. A sentence above the windows instructed the subject which aspect of the movement of the adjustable square should match that of the constant one. The arrows indicate the direction of movement of the squares and the background.

2.3 *Procedure*

The experiment was designed to distinguish between judging time-to-contact on the basis of optical variables and judging time-to-contact on the basis of perceived distance and perceived velocity. We asked subjects to match the final distances of the two squares from the bar, their velocities, or their time-to-contact with the bar by positioning the computer mouse. The squares were presented simultaneously for 1.3 s, with only the windows and the background visible for 1.3 s between presentations. This sequence was repeated until the subject was satisfied with the setting, and pressed a mouse button.

To investigate the effect of background motion on the perceived velocity of the squares, subjects were asked to match the velocities of the squares. In these trials, movement of the computer mouse changed the velocity with which the adjustable square moved. As the exposure time and final distance to the bar did not vary while the velocity was being adjusted, the initial position and time-to-contact were also changed by moving the mouse.

To investigate the effect of background motion on the perceived distance between the squares and the bar, subjects were asked to match the final distances of both squares. In these trials, the movement of the computer mouse changed the distance from the bar at which the adjustable square disappeared. As the exposure time and velocity did not vary while the final distance was being adjusted, the initial position and time-to-contact were again changed by moving the mouse.

The two other types of trials were designed to investigate the influence of background motion on the perceived time-to-contact. In these trials, movement of the computer mouse changed the time-to-contact between the adjustable square and the bar. The exposure time and velocity did not vary while the time-to-contact was being adjusted; the initial position and final distance from the bar were changed by moving the mouse. The movement of the constant square (and thus the time-to-contact) and the velocity of the adjustable square were exactly the same in trials with and without background motion.

To be able to compare the settings for the different matching tasks, we set the variable that was not under the subject's control during a trial to the average value (moving average of five trials) of the subject's settings when matching this variable. The position at which the adjustable square disappeared during the velocity-matching trials was the average position set in the distance-matching trials. The velocity at which the adjustable square moved in the distance-matching trials, and in both types of time-to-contact-matching trials, was the average velocity set in the velocity-matching trials. Although the physical velocities were the same in all time-to-contact-judging trials, the percept depended on the motion of the background. In trials with background motion, subjects perceived two squares moving with exactly the same velocity towards the bar, whereas in trials with a static background, the subjects perceived two squares moving at clearly different velocities.

The four matching tasks were repeated fifteen times in the same order: velocity (background moving), distance (background moving), time-to-contact (background static), time-to-contact (background moving). The first five cycles were used to build up the moving averages for the perceived equal final distance (used in velocity-matching trials) and the perceived equal velocity (used in distance-matching and time-to-contact-matching trials), and to give the subjects some practice in making the settings; the other ten cycles were analysed.

2.4 *Data analysis*

The experiment was designed to have a perceptually corresponding set of stimuli for each subject (for the moving-background condition). This allows us to give a quantitative prediction for the judged time-to-contact for both hypotheses mentioned in section 1. When a subject was asked to match the time-to-contact, the velocity of the adjustable square was chosen so that it appeared to the subject to move at the same speed as the constant square and to disappear at the same distance from the bar. To be able nevertheless to obtain this perceptual correspondence, velocities and final distances were set differently for different subjects. To compare the values of the time-to-contact settings across subjects, we therefore normalised the responses (the set time-to-contact of the adjustable square, t_a) on the basis of the actual time-to-contact of the constant square (t_c) and the set distance (x) and set velocity (v) of the adjustable square, resulting in a relative timing error (Δt) at the moment the target disappears:

$$\Delta t = \frac{t_a - t_c}{x/v - t_c}.$$

When the background is moving, the two hypotheses predict different values for Δt. If the *actual* (angular) velocity and distance (and thus the real time-to-contact) are used to match the timing ($t_a = t_c$), the relative timing error (Δt) will be zero. Thus, according to the τ hypothesis, the relative timing error will be zero. If the *perceived* velocity and distance are used to match the time-to-contact of the two squares (indirect perception hypothesis; $t_a = x/v$), the relative timing error will be 1. For the trials with a static background, both hypotheses predict a zero error.

In the trials on the judgment of time-to-contact, we asked subjects to match the time-to-contact of two squares, with and without background motion to the right. This could have induced directional biases in the judgments of time-to-contact. To eliminate any bias in the judgments, we did not test the predictions for the relative timing error itself, but the predictions for the changes induced by background motion. The τ hypothesis predicts that the relative timing error will not change; the indirect-perception hypothesis predicts that the relative timing error will increase by 1. The differences between these hypotheses and the experimental data were evaluated by means of t-tests on the effect of background motion on the relative timing error (95% confidence level).

An effect of our procedure is that the individual values for the relative timing error are not independent. Therefore, we cannot calculate standard deviations and test the hypotheses for individual subjects. Instead, we evaluated whether the background motion had a significant influence on the judgments of distance, velocity, and time-to-contact across subjects.

3 Results

Our twelve subjects were able to match the distance from the bar at which the two squares disappeared quite accurately (figure 2a). They set the final position of the adjustable square at an average distance of 3.9 cm from the bar, which was not significantly different from the final distance of the constant square (4 cm). When they were asked to match the velocities of the two squares, they set the velocity of the adjustable square at 2.9 cm s^{-1}, which was significantly different from the velocity of the constant square (5 cm s^{-1}, figure 2b). The systematic errors were in the direction that we expected: the velocity they perceived lies (for all but one subject) between the actual velocity and the velocity relative to the background.

For each subject, we calculated the relative timing error (Δt) in judging time-to-contact according to the formula presented in section 2.4. The twelve subjects' values for Δt are shown in figure 3. The absolute error that corresponded with a relative timing error of 1 ranged from 0.2 s for the subject with the smallest influence of the background on the perceived velocity (BB) to 3.3 s for the subject with the largest influence (RM).

When the background was stationary, subjects made systematic errors in matching the time-to-contact of the two squares of up to 400 ms (subject AL). On average, the *magnitude* of the error was 85±63 ms (average ± SEM). These errors were not systematic across subjects; some subjects overestimated while others underestimated the time-to-contact of the adjustable square. Averaged over subjects, the relative timing error was 0.04 ± 0.16.

Motion of the background had a systematic effect on matching time-to-contact; all subjects set a too high time-to-contact for the adjustable square, because it appeared to move faster than it was actually moving. On average, the relative timing error was 0.80 ± 0.09, which is slightly less than would be expected if the subjects had relied entirely on the perceived distance and velocity of the squares. The effect of background motion was significantly different from zero, so the τ hypothesis can be rejected. The effect of the moving background on the relative timing error did not differ significantly from 1, so we cannot reject the hypothesis that subjects use the perceived distance and velocity to judge time-to-contact.

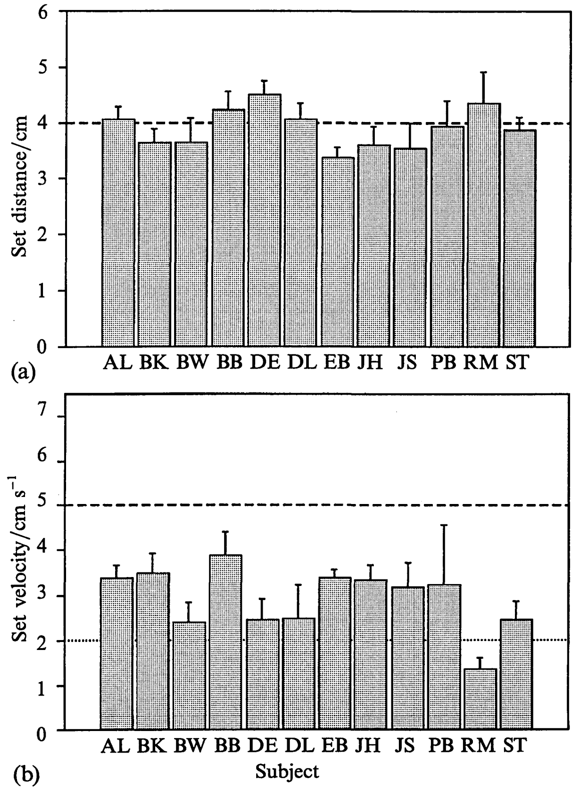

Figure 2. The results for matching distance and velocity. For each subject, we show the average ($\pm$SD) of ten settings. (a) The average distance from the bar at which subjects set the adjustable square to disappear in order for its final distance to appear to be equal to that of the constant one. The constant square always disappeared at 4 cm from the bar (dashed line). There was no systematic influence of background motion. (b) The average velocity at which subjects set the adjustable square to move for its velocity to appear to be equal to that of the constant one. All subjects underestimated the velocity of the constant square and overestimated the velocity of the adjustable squares, owing to the motion of the background. The actual velocity of the constant square was 5 cm s^{-1} (dashed line). If subjects had matched the velocities of both squares relative to the background, they would have set the velocity of the adjustable square to 2 cm s^{-1} (dotted line), so that each square would move at 3.5 cm s^{-1} relative to the background.

4 Discussion

The main result of the experiment is that background motion changed the perceived time-to-contact about as much as one would expect if subjects only used perceived velocity and perceived distance. The influence of background motion on the perceived distance and velocity were similar to those reported by Smeets and Brenner (1995); background motion changed the perceived velocity, but left the perceived position (ie distance) unchanged. The mechanisms by which a moving background changes the perceived velocity of a moving target is rather complex (eg Brenner and van den Berg 1994). We will not discuss this here, because this mechanism is irrelevant for our conclusion. Our approach requires a systematic change in perceived velocity. This systematic change enters the formula for the relative timing error as a change in v, which will give $\Delta t = 1$ if v is used to determine time-to-contact.

For one subject (AL), the relative timing error was 1, irrespective of background motion. This result could be due to an experimental artefact; we did not vary the final distance independently of the time-to-contact. When our subjects were matching time-to-contact, they changed the final distance of the adjustable square. If subjects had

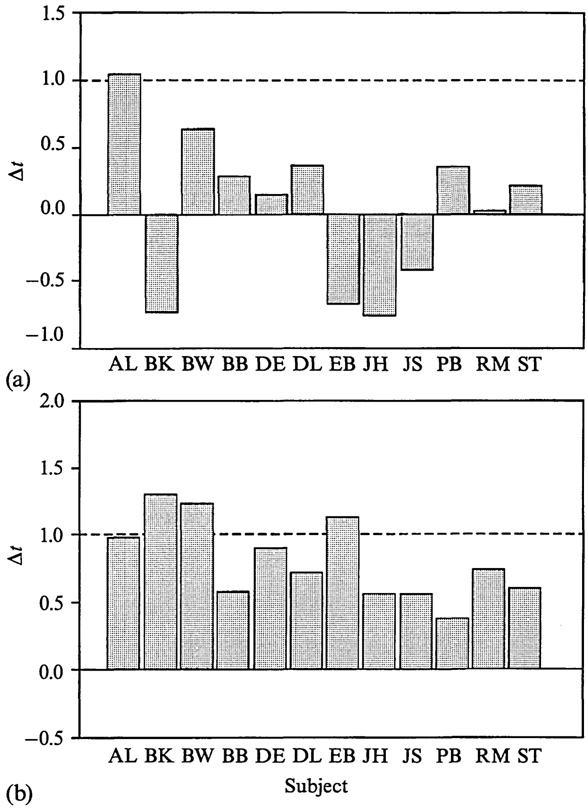

Figure 3. The results for matching time-to-contact. For each subject, we present the average relative timing error, Δt, for ten trials. (a) When the background was static, subjects were able to match the time-to-contact of the adjustable square to that of the constant one. Constant and adjustable squares were (correctly) seen to move at different speeds. Subjects made considerable errors, but these were not systematic across subjects. (b) Same task and velocities as in (a) but motion of the background changed the perceived velocities of the constant and adjustable squares so that they appeared to be equal (but in opposite directions). This change in apparent motion changed the judgment of time-to-contact significantly in the predicted manner.

not followed the instruction to match time-to-contact, but matched the distances instead, they would always get a relative timing error of 1. This strategy could explain the result of AL.

The main problem in interpreting experiments on time-to-contact in terms of optical variables (eg the relative rate of constriction) is that the actual time-to-contact is determined by the ratio of the distance and velocity of the object. Any combination of variables that describes this ratio will therefore be correlated with these two variables, and thus with the subject's performance. The only way to decide which variables are used is to vary them independently, and thus to violate physics. Our hypothesis, however, is not based on optical variables. Manipulating the perceived velocities of the squares independently of the actual movement (and thus of the rates of constriction) enabled us to show that subjects use the perceived velocity to estimate time-to-contact.

We used laterally moving objects. In this geometry, background motion is an excellent tool for changing the apparent motion of a target without changing the actual motion (Brenner 1991; Smeets and Brenner 1994). For the more general three-dimensional (3-D) situation, our hypothesis is that subjects use the ratio between perceived 3-D distance and perceived 3-D velocity, instead of local τ, angular velocity and angular distance. We cannot use background motion to discriminate between the two hypotheses in the 3-D situation, as the perceived velocity is hardly influenced by motion of the background (Brenner et al 1996). However, manipulation of other visual cues, such as vergence and relative disparity, can change the perceived distance and motion in depth, without changing the rate of optical expansion (Regan et al 1986; Heuer 1987; Brenner et al 1996).

It follows from our hypothesis that these results on the perception of distance and velocity imply that judgments of time-to-contact should be susceptible to changes in binocular information. By explicitly changing the target vergence independently from the optical expansion, Heuer (1993) showed that judgments of time-to-contact indeed depend on both optical expansion and changing target vergence. The data of Savelsbergh et al (1991) show that changes in the optical expansion (due to change in ball size) have a much stronger effect when viewed monocularly than when viewed binocularly. This is probably because a smaller part of the expansion is attributed to motion in depth in the presence of conflicting binocular information (Brenner et al 1996). One cannot explain the results of Savelsbergh et al (1991) and Heuer (1993) if one assumes that subjects only use τ to judge time-to-contact with approaching objects. They are easily explained if one follows our suggestion that the ratio of perceived distance and perceived velocity is used. Thus, we believe that our alternative hypothesis applies to all judgments of time-to-contact.

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