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Author(s)	Tayama, Tadayuki; Sato, Fumiaki
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Minimum temporal thresholds for discriminating changes in motion direction[1]

Tadayuki TAYAMA and Fumiaki SATO

Abstract: Minimum temporal thresholds (T_{min}) for discriminating motion direction were measured in various conditions. The results of Experiment 1 showed that T_{min} for the change from a stationary pattern to a moving pattern was shorter than that for the abrupt appearance of a moving pattern. The time needed to process the pattern explained this difference. The results of Experiment 2 showed that T_{min} for the change from a stationary pattern to a moving pattern was shorter than that for the directional change of a moving pattern. Furthermore, T_{min} for discriminating a directional change with a 90 deg difference was shorter than that of 45 and 135 deg. In addition, an anisotropy in discriminating motion direction was observed between oblique-upward and oblique-downward directions. The validity of mathematical models that explain these results was discussed.

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Keywords: Motion perception, Motion threshold, Motion discrimination, Motion detection, Perception of change

The present study examines the discrimination of change in motion direction. The concept of this area of study is similar to that of motion detection. In detection studies, displacement thresholds (D_{min}) and velocity thresholds (V_{min}) are often measured. These studies have shown that D_{min} are constant at approximately 1 or 2 min in a short temporal range, and there is a reciprocal relationship between V_{min} and time (Johnson & Leibowitz, 1976; Johnson & Scobey, 1980; Boulton, 1987; Tayama, 2000).

While there are few studies of the discimination of motion change, numerous studies investigated the detection of motion change by measuring reaction time (RT) (e.g., Tynan & Sekuler,

1 Corresponding concerning this article should be addressed to T. Tayama, Department of Psychology, the Graduate School of Letters, Hokkaido University, N10W7, Kita-ku, Sapporo, 060-0810, Japan. (E-mail: tayama@let.hokudai.ac.jp)

Tadayuki TAYAMA: tayama@let.hokudai.ac.jp
Fumiaki SATO: fsato@me.com
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1982; Sekuler, Sekuler, & Sekuler, 1990; Hohnsbein & Mateeff, 1992; Dzhafarov, Sekuler, & Allik, 1993; Mateeff, Genova, & Hohnsbein, 1999; Kreegipuu & Allik, 2007). These studies showed that RT to the onset of a moving stimulus increases with eccentricity (Tynan & Sekuler, 1982), RTs to the onset and offset of moving stimuli decrease with stimulus speed but the reduction in onset was larger than that in offset (Hohnsbein & Mateeff, 1992), and RT to changes in moving direction decreases with the angle of the difference between two directions (Mateeff, Genova, & Hohnsbein, 1999). Sekuler, Sekuler, & Sekuler (1990) also showed that the directional uncertainty of the initial stimuli did not affect RTs to changes in motion direction if the duration were more than 500ms.

In these studies, Pieron function, as shown in Formula (1) (Piéron, 1920), was often used to fit to RT data (e.g., Mateeff, Genova, & Hohnsbein, 1999; Genova, Mateeff, Bonnett, & Hohnsbein; 2000).

$$RT = C/S^n + RT_0 \qquad (C>0,\ n>0,\ RT_0>0) \qquad (1)$$

In this formula, RT_0 is the time needed to complete a motor skill, S is the stimulus intensity, and C and n are constants that vary with individuals. Some studies showed clear evidences of the difference between simple reaction time (SRT) and choice reaction time (CRT). For example, Genova, et. al. (2000) showed that while SRT decreased as the angle difference between two directions increased, the relationship between CRT and angle difference displayed a U-shaped curve and the CRT minimum was approximately at 90 deg. Mateeff, Genova & Hohnsbein (2005) also found the difference between SRT and CRT by combined changes of speed and direction. As for CRT, Mateeff, et al. (2005) found that Formula (2) provided a good fit to the data. In this formula, if the first stimulus (V_1) changed to the second stimulus (V_2), V_{2N} is an element of V_2 perpendicular to V_1.

$$CRT = C/(V_{2N})^n + CRT_0 \qquad (C>0,\ n>0,\ CRT_0>0) \qquad (2)$$

Although these RT studies have revealed reliable results, they have a problem of RT_0, which is time required for a motor skill and is unrelated to perception. Therefore, RT_0 is desirable to be removed, if possible. For this reason, some studies have used different methods of measuring time to discriminate change (Mateeff, Dimitrov & Hohnsbein, 1995; Tayama, 2000; Lappin, Tadin, Nyquist & Corn, 2009; Tadin, Lappin, Blake & Glasser, 2010). For example, Tayama (2000) used a two-AFC method to measure the minimum time (T_{min}) needed to discriminate horizontal directions in moving Gabor patterns and showed also that T_{min} decreased as speed increases. Lappin, et al. (2009) also used the same method to examine the motion discrimination across variations in speed, eccentricity and low vision and found similar results. Both studies showed the similar results but there is a great difference between them. While Lappin, et al. (2009) measured T_{min} in the broad range of speed (0.06 to 30 deg/s), Tayama (2000) measured with slow speeds (0.78 to 2.5 deg/s). Considerable evidence showed that there is a difference between sensitivities to slower and higher speed and that position sensitivity is related to slower speed, while the sensitivity to temporal frequency is related to higher speed (Tyler & Torres, 1972; Mandler & Makaous, 1984; Wright, 1987; Lappin, et al., 2009). The present study is in line with Tayama(2000) and focuses on the ability to discriminate the direction of motion with very slower speed (less than 1.4 deg/s), which will be related to position sensitivity. Tayama (2000) found that if temporal constant (T_{const}) was subtracted from T_{min} and the value was multiplied by speed(V), then the resulting spatial value was fixed at approximately 1 min (D_{const}). He assumed that T_{min} required to discriminate the moving direction is automatically determined by two constants: temporal (T_{const}) and spatial (D_{const}), which is denoted by Formula (3). This formula can be transformed into Formula (4).

$$V(T_{min} - T_{const}) = D_{const} \quad (3)$$

$$T_{min} = D_{const}/V + T_{const} \quad (4)$$

Formula (4) can be compared with Formula (2). Mateeff et al. (2005) showed that CRT data provide the best fit to Formula (2) when n is 0.39～0.53, whereas Tayama (2000) showed that T_{min} data provide the best fit to Formula (4) when T_{const} is 35 ms and D_{const} is 1 min. These formulae are similar but there are three differences between them. First, the exponent in Formula (2) is set to n, but the exponent is excluded (i.e., n=1.0) in Formula (4). Second, Formula (2) contains CRT_0, the time needed to complete a motor skill, whereas Formula (4) contains T_{const}, which is not relevant to motor skills. Third, Formula (2) accounts for RT changes with the angle difference between V_1 and V_2, but Formula (4) does not consider this angle change. The first difference between these formulae is crucial, because the remaining differences only reflect contrasts between the tasks.

It is obvious that the fitting of CRT data to Formula (2) defined by three constants (C, n, CRT_0) is better than to Formula (4) defined only by two constants (T_{const} and D_{const}). However, if the same data can be explained by a model that contains fewer variables, it is preferable. Therefore, the present study investigates to what extent Formula (4) are applicable to the experimental data that discriminate directional change. Mateeff et al. (2005) used the exponent n in Formula (2) to apply the Pieron function to their data, but there does not seem to be a definite reason for using this exponent or assumptions about the process that corresponds to each variable. On the other hand, T_{const} and D_{const} in Formula (4) were inferred from experimental data in the previous study (Tayama, 2000) and the exponent n was excluded from the beginning. The assumptions are that T_{const} and D_{const} likely denote temporal processing and spatial processing, respectively, that T_{const} is related to processing of V_1 (e.g. processing of a stimulus pattern) and D_{const} is related to processing of V_2, and that the time for discriminating the motion direction of change is basically determined by these two constants. If these assumptions are correct, the following three predictions can be derived. The purpose of the present study is to examine the validity of these by measuring T_{min} required to discriminate the motion direction in the selected conditions.

First, we can predict from Formula (4) that if V_1 is presented before V_2 regardless of whether V_1 is stationary or in motion, less time is needed to process the stimulus pattern, then T_{const} approaches zero seconds. Consequently, T_{min} will be small. On the other hand, if V_1 is not presented and V_2 is abruptly presented, T_{const} will increase, because more time is needed to process the pattern. Consequently, T_{min} will be large. Thus, T_{min} to discriminate the motion direction of V_2 should vary based on whether V_1 was presented. Experiment 1 will test this prediction (Prediction 1).

Second, we can predict from Formula (4) that if T_{const} is related to the time needed to process the stimulus pattern or something related to V_1, the value of T_{const} will be influenced by whether V_1 is stationary or moving, but D_{const} will not be influenced by that. As a corollary, we also predict that T_{const} for the stationary V_1 will be smaller than that of the moving V_1, because the time to detect motion change decreased as the difference in speed increased (Mateeff et al., 1995) and the speed difference in the former will be larger than that in the latter. Experiment 2 will test this prediction (Prediction 2).

Third, we consider the influence of the angle difference between V_1 and V_2 on the discrimination of the direction of change. Formula (2) supposes that T_{min} varies with the angle difference between V_1 moving in the vertical direction and V_2, based on the speed of the horizontal element of V_2. If we adopt this idea, Formula (4) will be transformed into Formula (5).

$$T_{min} = D_{const}/V_{2N} + T_{const} \tag{5}$$

Here, V_{2N} is the horizontal element of V_2 perpendicular to V_1. We can predict from Formula (5) that T_{min} varies with the angle difference between V_1 and V_2, which is based on the variability of D_{const}. If D_{const}/V_{2N} were constant, D_{const} would vary with the angle difference between V_1 and V_2. Then, D_{const} will be smallest when the angle difference is 90 deg, if the same minimum horizontal element is crucial for discrimination. Experiment 2 will also test this prediction (Prediction 3).

The present study is characterized by measuring T_{min}, which does not need to consider RT_0 for a motor skill, by comparing experimental data with the predictions derived from the simple Formulae, and by verifying the validity of the assumptions. In the following experiments, T_{min} is measured using foveal vision and a slow stimulus speed without cues of reference stimuli. These conditions are similar to those of Tayama (2000) and are important variables with regard to T_{min}. Under these conditions, it is known that D_{min} ($= T_{min} \times V$) should be 1 or 2 arc min (e.g., Johnson & Scobey, 1980; Tayama, 2000).

Experiment 1

Method

Observers

Four graduate students and one of authors participated in this experiment. All observers had normal visual acuity (either uncorrected or corrected by glasses).

Stimuli and apparatus

A personal computer (Apple, Power Macintosh G4 Cube) and a 17-inch display monitor (Sony, Multiscan 17 SEII) were used to present stimuli. Test patterns were presented on the center of the monitor (Figure 1a) and controlled by the computer. These were plaid patterns, which were composed of two sinusoidal gratings with a spatial frequency of 1.0 c/deg. Each grating was oriented +45 deg and −45 deg from vertical. The moving speed of pattern was controlled by the size of displacements from one frame to the next frame, keeping frame rate constant at 100 Hz. The mean luminance of the test pattern was 6.0 cd/m^2, and the contrast was 30%. The size of the test field was 2.56 deg × 2.56 deg (3.8 cm × 3.8 cm). The test field was fixed and did not move.

A Gaussian filter[2] blurred the peripheral area of this field so that the observer could not use the luminance changes at the stimulus edge to make discrimination judgments. However, to indicate the presentation position of the test pattern on the monitor, four small red dots were presented on the top, bottom, left, and right positions against a background of the center of the test field (Figure 1a). The distance between the center and each dot was 1.27 deg. Observers were asked to gaze at the center of these dots with binocular vision. The test patterns consisted of V_1 and V_2 (Figure 1b) and were presented consecutively at the same location. When the test patterns changed from V_1 to V_2, the plaid phase of V_2 was inherited from V_1. This means that the phase gap could not be used as a cue to discriminate direction. The computer controlled the motion speed of the test patterns and the presentation time. The luminance of the background was 6.0 cd/m^2. The observing distance was 85 cm. The experiment was conducted in a dark room.

Experimental conditions

There were two V_1 conditions. The V_1 was either present or absent (Figure 1b). In the V_1-to-V_2 condition, the stationary plaid pattern (V_1) was presented and changed to the moving plaid pattern (V_2). In the no-V_1 condition, V_1 was not presented, and V_2 moving plaid pattern was abruptly presented. The moving direction of V_2 was fixed horizontally. There were four V_2 speed conditions for each V_1 condition: 0.175 deg/s, 0.35 deg/s, 0.70 deg/s, and 1.4 deg/s. There were eight experimental conditions, two V_1 conditions crossed with four speed conditions in all.

Procedure

A transformed up-down method measured T_{min} for each condition across a sequence of trials. The experiment was conducted for each V_1 condition. In the no-V_1 condition, the observer only viewed V_2 and judged whether it moved to the right or left. In the V_1-to-V_2 condition, the observer viewed the stationary V_1 for 640 ms followed by the moving V_2 and judged its motion direction. The horizontal direction (right or left) of V_2 was randomly determined for each trial, but the probability that each direction would occur was fixed at 50%. In the initial trial, the duration of V_2 for each condition lasted long enough to make a clear judgment of the motion direction. In a preliminary experiment, an approximate T_{min} was measured for each condition by directly adjusting the duration of V_2. Twice the value of the approximate T_{min} was set as the initial duration of V_2 in this experiment. The observer judged motion direction by pushing one of two keys. There was no feedback for the response. The length of the duration of V_2 in each trial was varied by the following method. If two judgments were correct in succession for the same duration of V_2, then the duration decreased one unit of time in the next trial. If a judgment was incorrect once for the test duration, then the duration of V_2 was increased one unit of time for the next trial. Theoretically, this method causes the durations to converge to 71% thresholds

2 The function of Gaussian filter is expressed by $\exp(-(x^2/2\delta^2+y^2/2\delta^2))$, where x and y indicate the coordination and δ indicates one variable parameter of this function. Stimuli used in this experiment were composed by superimposing two Gabor patterns (by adding two luminance in each pixel). Gabor function is expressed by $\sin(2\pi f_x x)\cdot\exp(-(x^2/2\delta^2+y^2/2\delta^2))$ if the pattern is vertical, where f_x indicates the spatial frequency. Each Gabor was rotated and oriented +45 deg and −45 deg from vertical. The appropriate value of δ was selected to make the edge blurr.

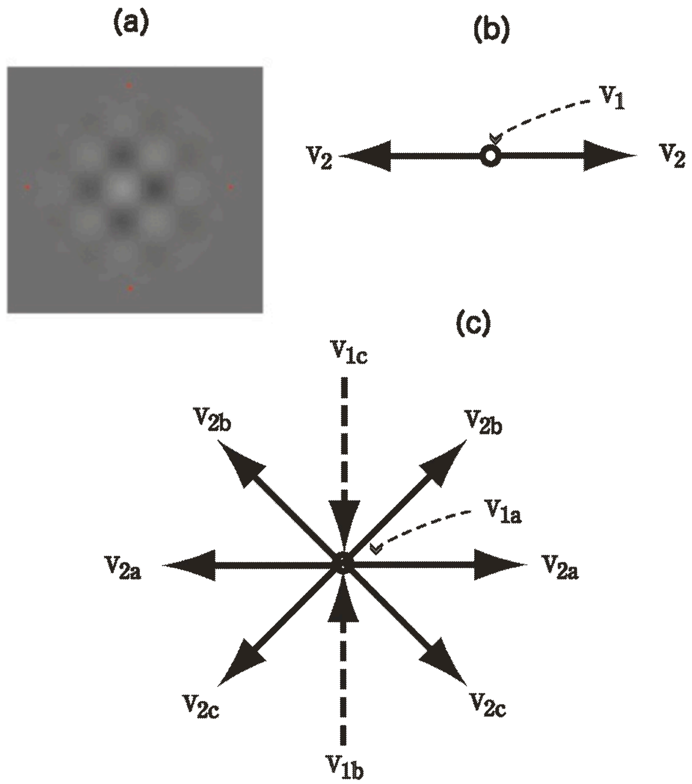

Figure 1. The stimuli used in experiments. (a) Gabor patch. (b) Stationary stimuli (V_1) to moving stimuli in a horizontal direction (V_2) in Experiment 1. (c) Stationary (V_{1a}) or moving stimuli (V_{1b} or V_{1c}) in a vertical direction to moving stimuli in horizontal (V_{2a}) or oblique directions (V_{2b} or V_{2c}) in Experiment 2.

(Levitt, 1970). One unit of time was 30 ms when the duration of V_2 was more than 100 ms and 10 ms when the duration of V_2 was less than 100 ms. The trials for one measurement were finished when observers completed ten reversals from decreasing trials to increasing trials and vice versa. Six duration values of V_2 corresponding to the last six reversals were averaged and recorded as T_{min}. The T_{min} for the four speed conditions in one of the V_1 conditions were measured in random order, and each observer repeated this procedure three times consecutively. This is one session. Each observer completed one session consecutively for another V_1 condition. The order of the V_1 conditions was randomized. Observers had a short rest between sessions.

Results and Discussion

The mean T_{min} of each condition for each observer was calculated. A 4×2 repeated measured ANOVA was performed on the values with respect to speed and V_1 (present or absent). Only the main effect of speed was significant ($F(3, 32)=24.384$, $p=.000$). Subsequent tests showed that the differences of mean T_{min} between speed conditions, except between 0.35 and 0.70 deg/s and between 0.70 and 1.40 deg/s, were significant (Tukey's HSD test, $p<0.026$). The mean T_{min} for each condition was plotted as a function of speed (Figure 2a). The results of one observer (TT) are also shown in Figure 2c for reference. The fitting curves of the inverse function are shown in these figures. In both V_1 conditions, T_{min} decreased as speed increased. Thus, motion directions with higher velocities were judged more quickly.

Next, D_{min} was computed by multiplying T_{min} by the speed and the mean D_{min} of each condition for each observer was calculated. A 4×2 repeated measured ANOVA on the values showed that the main effects of speed, V_1 and the interaction were significant (respectively, $F(3, 32)=8.733$, $p=.000$; $F(1, 32)=16.234$, $p=.000$; $F(3, 32)=4.003$, $p=.016$). Subsequent tests showed that the differences of mean D_{min} between 1.40 deg/s and other speeds were significant (Tukey's HSD test, $p<0.023$). The mean D_{min} for each condition was plotted as a function of speed (Figure 2b). Figure 2d shows the results of one observer. In these figures, 4 points in each V_1 condition are on a straight line with a certain slope. A straight line produced by the least-squares method and the formula of the relationship between D_{min} and speed are also shown in this figure. Transforming these formulae into the style of Formula (3) because of examining our predictions, the following formulae (6) and (7) were obtained for the no-V_1 condition and the V_1-to-V_2 condition, respectively.

$$V(T_{min}-0.042)=0.023 \tag{6}$$
$$V(T_{min}-0.009)=0.025 \tag{7}$$

In the above formulae, the values corresponding to T_{const} in Formula (3) are 42 ms for the no-V_1 condition and 9 ms for the V_1-to-V_2 condition (these formulae used seconds as the unit). The T_{const} for the V_1-to-V_2 condition was close to zero. According to Tayama (2000), these T_{const} indicate the minimum time required to process a pattern. On the other hand, the values corresponding to D_{const} in Formula (3) are 1.38 min (0.023 deg) for the no-V_1 condition and 1.5 min (0.025 deg) for the V_1-to-V_2 condition. The D_{const} is the minimum displacement required to identify the motion direction. The D_{const} values are almost the same. Therefore, T_{const} difference between the two V_1 conditions was large but the D_{const} difference was small in this experiment. Accordingly, T_{min} for the V_1-to-V_2 condition was shorter than that of the no-V_1 condition. These results clearly support Prediction 1.

In this experiment, T_{min} for discriminating the motion direction in the V_1-to-V_2 condition was shorter than that in the no-V_1 condition. This difference seems to be based on the 33-ms difference in T_{const}. The T_{const} for the no-V_1 condition in Experiment 1 was 42 ms, whereas T_{const} for the no-V_1 condition was 35 ms for Tayama (2000). These values are similar even after considering the differences in observers and stimuli. Tayama hypothesized that 35 ms is required to process patterns from presentation onset. The T_{const} difference between the V_1 conditions obtained in this experiment supports this hypothesis but the validity of this hypothesis will be discussed later again.

In the next experiment, we measured the time needed to discriminate motion direction using the same method as Experiment 1, except that V_1 was either stationary or moving vertically, and V_2 was moving either horizontally or obliquely, and examined Predictions 2 and 3.

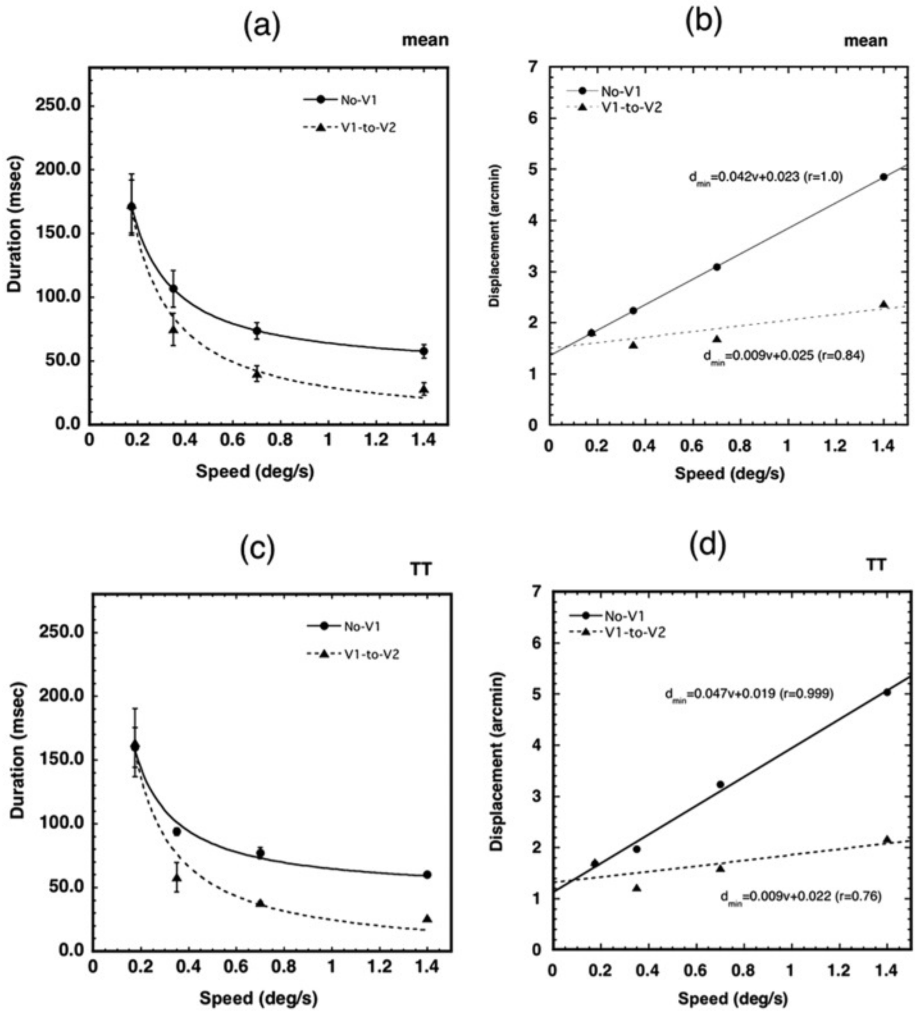

Figure 2. (a) Mean duration threshold (T_{min}) and (b) mean displacement threshold (D_{min}) for motion discrimination as a function of speed. The parameter indicates V_1 condition. The error bar shows ± standard error of threshold. (c) and (d) are observer results (TT).

Experiment 2

Method

Observers

Three undergraduate students participated in this experiment. All observers had normal visual acuity either uncorrected or corrected by glasses.

Stimuli and apparatus

Unlike Experiment 1, all stimuli changed from V_1 to V_2. While V_1 was stationary or moved in the vertical directions, V_2 moved in the horizontal or oblique directions. Except these, the stimuli and apparatus were the same as those used in Experiment 1.

Experimental conditions

There were three V_1 conditions. V_1 was either stationary (as in Experiment 1) or moved vertically (V_{1a}, V_{1b}, and V_{1c} in Figure 1c). There were also three V_2 conditions: V_2 moved in a horizontal direction, or in an oblique-upward direction, or in an oblique-downward direction (V_{2a}, V_{2b}, and V_{2c} in Figure 1c). The oblique direction was 45 deg from horizontal. When V_1 moved, the speed was the same as that of V_2. The four speed conditions were the same as in Experiment 1. There were 36 experimental conditions in all.

Procedure

The T_{min} for each condition was measured using the same method as that for the V_1-to-V_2 condition in Experiment 1. This experiment was conducted consecutively for each V_2 condition. First, observers viewed V_1 for 640 ms and then viewed V_2, and judged the motion direction of V_2. They judged whether it moved to the right or left. The criterion for judgments was the same for all V_2 conditions. Observers judged right or left even in the oblique V_2 conditions. The direction of V_2 (right or left) was randomly determined for each trial, and the probability for each direction was fixed at 50%. The T_{min} were measured consecutively for 12 conditions (i.e., three V_1 conditions by four speeds) in a random order. This is one session and a short rest was inserted between sessions. Each observer judged motion direction for three V_2 conditions in a random order in a total of 36 experimental conditions (three sessions) in one day. This procedure was repeated four times in different days.

Results and Discussion

The mean T_{min} of each condition for each observer was calculated. A 3×3×4 repeated measured ANOVA was performed on the values with respect to V_1, V_2 and speed. The main effects of V_2 and speed were significant (respectively, $F(2, 72)=7.339$, $p=.001$; $F(3, 72)=78.267$, $p=.000$). Subsequent tests for V_2 showed that the differences of mean T_{min} between oblique-upward and horizontal directions were significant (Tukey's HSD test, $p=0.001$). Subsequent tests for speed showed that the differences of mean T_{min} in any combination, except between 0.70 and 1.40 deg/s, were significant (Tukey's HSD test, $p<0.001$). Next, D_{min} was computed by multiplying T_{min} by the speed and the mean D_{min} of each condition for each observer was calculated. A 3×3×4 repeated measured ANOVA on the values showed that the main effects of V_2, speed and the interaction between V_1 and V_2 were significant (respectively, $F(2, 72)=13.653$, $p=.000$; $F(3, 72)=11.766$, $p=.000$; $F(4, 72)=2.968$, $p=0.025$). Subsequent tests for V_2 showed that the differences of mean T_{min} between oblique-upward and horizontal directions ($p=0.001$) and between oblique-downward and horizontal directions ($p=0.016$) were significant. Subsequent tests for speed showed that the difference of mean D_{min} between 1.40 deg/s and other speed conditions were significant (Tukey's HSD test, $p<0.002$).

Comparison of V_1 conditions

The data for V_2 conditions were pooled, and the mean T_{min} was calculated for each V_1 condition. These results are shown as a function of speed in Figure 3a, the form being the same as that in Figure 2a. The results showed that T_{min} decreased with speed in all V_1 conditions with no difference between them. Next, D_{min} was calculated by multiplying T_{min} by speed and plotted as a function of speed (Figure 3b), with the form the same as that of Figure 2b. This figure shows a clear difference among V_1 conditions. By transforming the linear relationship between D_{min} and speed into the style of Formula (3) using the least squares method, we obtained Formulae (8), (9), and (10) for the stationary, upward, and downward conditions of V_1, respectively.

$$V(T_{min}-0.007)=0.028 \tag{8}$$

$$V(T_{min}-0.017)=0.026 \tag{9}$$

$$V(T_{min}-0.015)=0.028 \tag{10}$$

In these formulae, the values that correspond to T_{const} in Formula (3) are 7 ms for the stationary condition and 15 ms and 17 ms for the upward and downward conditions, respectively. Compared with the 42 ms observed in the no-V_1 condition in Experiment 1, all of these values were small. However, T_{const} of the stationary V_1 was less than half the size of that of the moving V_1. On the other hand, D_{const} ranged from 1.56 min (0.026 deg) to 1.68 min (0.028 deg), which was almost the same in any V_1 condition. Therefore, T_{min} for the stationary V_1 was lower than that for the moving V_1 because of the speed difference, but we can think that T_{min} varied based on the values of T_{const}. These support Prediction 2.

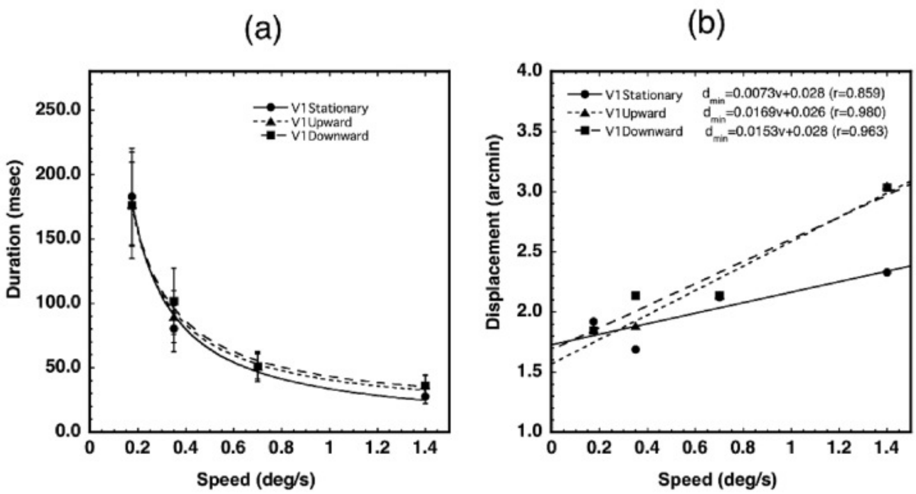

Figure 3. (a) Mean duration threshold (T_{min}) and (b) mean displacement threshold (D_{min}) for motion discrimination as a function of speed. The parameter indicates the V_1 condition. The error bar shows ± standard error of threshold.

Comparison of V_2 conditions

The data for the V_1 conditions were pooled, and the mean T_{min} were calculated for each V_2 condition. The results are shown in Figure 4a. This figure shows the differences among the moving V_2 directions. The T_{min} decreased with speed in all V_2 conditions. However, T_{min} for the horizontal direction was smaller than that of the oblique-downward motion, which was, in turn, smaller than that of the oblique-upward motion. The D_{min} results are shown in Figure 4b. This figure shows clear differences among the V_2 conditions. The linear slopes determined by the least squares method are almost the same across all V_2 conditions. By transforming the linear relationships between D_{min} and speed into the style used for Formula (3), Formulae (11), (12), and (13) were obtained for the horizontal, oblique-upward, and oblique-downward V_2 conditions, respectively.

$$V(T_{min}-0.013)=0.021 \tag{11}$$
$$V(T_{min}-0.014)=0.034 \tag{12}$$
$$V(T_{min}-0.013)=0.028 \tag{13}$$

These formulae show that T_{const} were fixed from 13 to 14 ms. These values are relatively small although not as small as the 9 ms in the stationary V_1 condition of Experiment 1 (Formula (7)) or the 7 ms in the stationary V_1 of Experiment 2 (Formula (8)). The result that T_{const} were almost the same across all V_2 conditions means that V_2 motion direction was not relevant to T_{const} values. On the other hand, D_{const} varied across V_2 conditions. These values were 1.26 min (0.021 deg), 2.04 min (0.034 deg) and 1.68 min (0.028 deg) for the horizontal, oblique-upward, and oblique-downward directions, respectively.

The horizontal elements of D_{const} ($=D_{const}\times V_{2N}/V_2$) based on Formula (5) were 1.19 min ($=1.68/\sqrt{2}$) for the oblique-downward direction and 1.44 min ($=2.04/\sqrt{2}$) for the oblique-upward direction. The former is quite similar to that (1.26 min) for the horizontal direction but the latter was relatively larger than those for other directions. This difference indicates an anisotropy such that a large displacement is required to discriminate the moving direction for the oblique-upward direction when compared with other directions. This result indicates that the variability of angle differences predicted by Formula (5) could not be applied to the present data. However, the findings that there was no difference in T_{const} among V_1 conditions, that there were differences in D_{const} among V_2 conditions, and that T_{min} vary with D_{const}, partly support Prediction 3. Together with the results of Judgments for V_1 conditions, these results suggest that the assumption that T_{const} and D_{const} concern the discrimination of motion direction in this order is basically correct.

Comparison of angle differences between two directions

We assume that if V_1 changes to V_2 with a large angle, the change will be easier to discriminate than a small angle change. However, Genova et al. (2000) showed that whereas the SRT in a detection task decreases with the angle difference between two directions, the CRT minimum in a discrimination task occurs at a direction difference of 90 deg. To confirm this, we eliminated the data for the stationary V_1 condition in Experiment 2. Next, we pooled the data of the upward

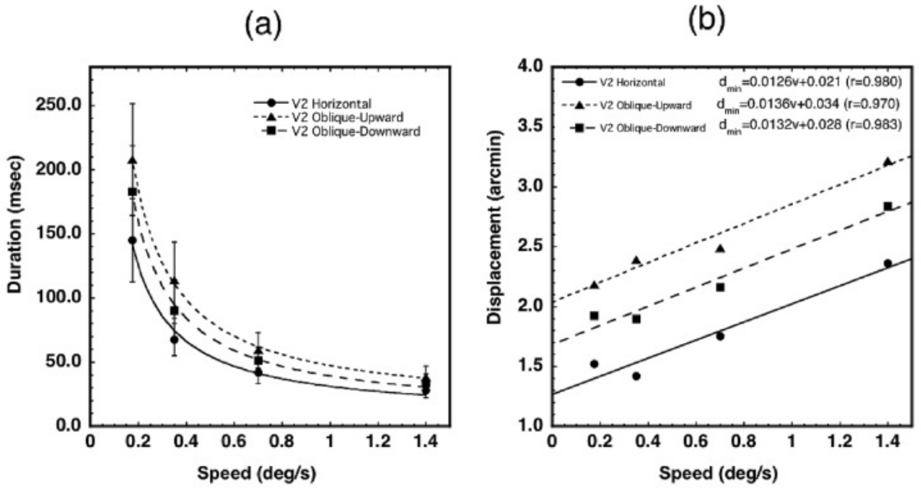

Figure 4. (a) Mean duration threshold (T_{min}) and (b) mean displacement threshold (D_{min}) for motion discrimination as a function of speed. The parameter indicates V_2 direction. The error bar shows ± standard error of threshold.

V_1 to the oblique-upward V_2 and the data of the downward V_1 to the oblique-downward V_2, considered as the conditions of 45 deg (small angle) and pooled the data of the upward V_1 to the oblique-downward V_2 and the data of the downward V_1 to the oblique-upward V_2, considered as the conditions of 135 deg (large angle). We also pooled the data of the upward V_1 and the data of downward V_1 to V_2 moving in a horizontal direction, considered as the conditions of 90 deg. The results of T_{min} and D_{min} for these conditions are shown in Figures 5a and Figure 5b, respectively. The figures show that both T_{min} and D_{min} in the 45-deg condition are larger than those of the 135-deg condition and the values for the 90-deg condition are the smallest. These results match those of Genova et al. (2000). By transforming the linear relationships between D_{min} and speed into the style used for Formula (3), we obtained Formulae (14), (15) and (16) for 45 deg, 90 deg, and 135 deg, respectively.

$$V(T_{min}-0.019)=0.034 \tag{14}$$
$$V(T_{min}-0.015)=0.019 \tag{15}$$
$$V(T_{min}-0.014)=0.029 \tag{16}$$

In these formulae, T_{const} decreased with angles (19 ms to 14 ms), but these changes were relatively small. On the other hand, D_{const} were 2.05 min (0.034 deg), 1.13 min (0.019 deg), and 1.71 min (0.029 deg) for 45 deg, 90 deg, and 135 deg, respectively. These differences are large (the minimum was 90 deg). The values of horizontal elements of D_{const} ($=D_{const}\times V_{2N}/V_2$) that correspond to 45 deg and 135 deg were 1.45 min ($=2.05/\sqrt{2}$) and 1.21 min ($=1.71/\sqrt{2}$), respectively. The value for 135 deg is almost the same as the value for 90 deg (1.13 min) but the value for 45 deg was larger than others. These results of the large difference in D_{const} and the small difference in T_{const} among different angles also support Prediction 3.

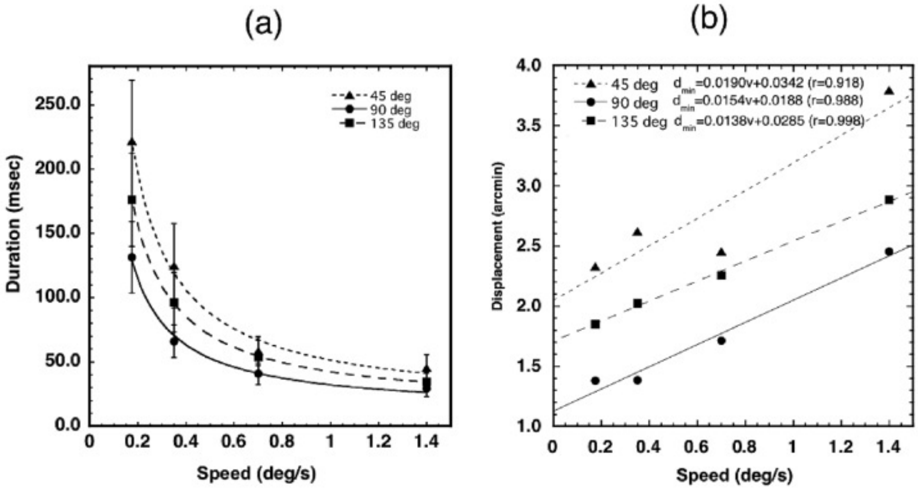

Figure 5. (a) Mean duration threshold (T_{min}) and (b) mean displacement threshold (D_{min}) for motion discrimination as a function of speed. The parameter indicates whether the directions of V_1 and V_2 are the same or opposed. The error bar shows ± standard error of threshold.

General Discussion

The effects of V_1 on motion discriminations

From Formula (4), we predicted that T_{const} varies dependent on the existence of V_1. If V_2 is abruptly presented, then T_{const} will increase because time is needed to process the stimulus pattern, and consequently T_{min} will increase. On the other hand, if V_1 changes to V_2, T_{const} will approach zero seconds because as long as V_1 exists, not as much time is needed to process the stimulus pattern, and consequently T_{min} becomes small. These results of Experiment 1 clearly support Prediction 1.

In Experiment 2, we compared the stationary V_1 condition with the moving V_1 condition. Because the difference of speed between V_1 and V_2 in the former is larger than that in the latter, T_{min} for discrimination in the former is thought to be smaller than the latter. This result matches Mateeff et al. (1995). As the background, we predicted that T_{const} values differed between the stationary and moving V_1 conditions and the value of the former would be smaller than that of the latter, but the values of D_{const} were almost the same. The results of Experiment 2 support this prediction (Prediction 2). Compared with T_{const} (42 msec) in the no-V_1 condition of Experiment 1 (Formula (6)), T_{const} in Formula (8) to (10) were small, but T_{const} in the stationary V_1 condition (7.3 msec in Formula (8)) was less than half of that in the moving V_1 condition (16.9 and 15.3 msec in Formula (9) and (10)). This suggests that so long as V_1 is present, the time required to process a pattern is small, but more time is required to discriminate the directions in the moving V_1 condition than that in the stationary condition. This difference in T_{const} might be that of time required to detect (not to discriminate) change. However, we still do not know clearly about the process involved in T_{const}. The temporal delay to detect change for the abrupt onsets in the no-V_1 condition might be brought by the interference based on the onset transients in luminance and contrast.

The effects of V_2 on motion discriminations

We predicted that T_{const} would not change with V_2 because T_{const} would approach zero seconds as long as V_1 was presented, and that T_{const} would be irrelevant to the direction of V_2 if T_{const} is related to the time needed to process the pattern (or V_1). In addition, we predicted that D_{const} would vary with the angle difference between V_1 and V_2 (Prediction 3). Thus, Prediction 3 consists of two parts: the prediction of T_{const} and the relation between D_{const} and the V_1/V_2 angle difference. Figure 4b shows that the slopes of the three parallel lines are almost the same, suggesting that although there is no difference in T_{const} or time required for processing pattern between them, D_{const} required to discriminate the direction of V_2 are different, as indicated in the difference of y-intercepts. As shown in Formulae (11) to (13), D_{const} varied with the direction of V_2, but T_{const} did not. These results support the first part of Prediction 3.

Mateeff et al. (2005) reported that T_{min} varies with the angle difference based on the intensity of V_{2N}, as indicated in Formula (2). This means that an imaginary line perpendicular to a vertical line becomes a criterion in judgments when V_1 moves vertically. To explore this possibility, we calculated the horizontal element (V_{2N}/V_2) of D_{const} for each V_2 direction condition. The results showed that the horizontal element of D_{const} for the oblique-downward direction was very close to that for the horizontal condition but was smaller than that for the oblique-upward direction. It seems that in the oblique -upward direction, larger spatial distance is needed to discriminate changes. This causes an anisotropy in the discrimination of changes in motion direction, which will be discussed later.

Thus, T_{min} differs depending on the angle between the V_2 direction and the vertical line, and the difference seems to be based on D_{const}. This result partly supports the second part of Prediction 3.

The influence of the angle difference between V_1 and V_2

Genova, et. al. (2000) showed that the time needed for discriminating a direction change from V_1 to V_2 varies with the angle difference. The minimum time was observed approximately at 90 deg. We analyzed T_{min} for each angle difference. The results (see Figure 5) revealed that T_{min} was the minimum when the angle difference was 90 deg (in the horizontal direction). The results also showed that the horizontal element (V_{2N}/V_2) of D_{const} for large angle (135 deg) was very close to that for the horizontal condition (90 deg), but was smaller than that for small angle (45 deg). This indicates that the discrimination for large change in angle is essentially equivalent to that in the horizontal direction but larger spatial distance is needed for discriminating small changes in angle. It is natural because observers would not easily perceive the change when the angle difference is small. However, the result that D_{const} varied with the angle difference between V_1 and V_2 also partly supports the second part of Prediction 3.

Anisotropy in the oblique direction

The anisotropy of discrimination of changes in the oblique direction was an unexpected result in this study. This is qualitatively different from the effect of angle difference on discrimination. The T_{min} and D_{min} in the oblique-upward direction were both larger than those in the oblique-downward direction (see Figure 4). However, although T_{const} in the oblique-upward direction was almost the same as that of the oblique-downward direction, D_{const} in the former was different from that of the latter (formulae (12) & (13)). This means that although the time required to process the pattern or to detect change was the same, the spatial distance required to discriminate direction varied upon whether V_2 moved upward or downward obliquely. Studies in motion perception have shown that sensitivity in the centrifugal direction is higher than that in the centripetal direction (e.g., Giaschi, Zwicker, Young, & Bjornson, 2007; Shirai, & Yamaguchi, 2004; Mateeff, Bohdanecky, Hohnsbein, & Ehrenstein, 1991; Perrone, 1986; Ball & Sekuler, 1980). The anisotropy obtained in the present study is different from this effect. However, there might be a relationship between the concepts. For example, if a moving object approaches a person, the downward optic flow will be more critical (sometimes fatal) than the upward optic flow (e.g., when driving a car). He will pay more attention to a movement that might hit him. Our visual system might have an evolved mechanism for discriminating the subtle differences in the downward optic flow. However, to verify this hypothesis, further experimentation is required.

Further investigations

Apart from the anisotropy in discrimination, the experimental results support three predictions of the present study. Thus, we can think that the assumptions regarding T_{const} and D_{const} from Formula (5) are broadly correct. However, the present study examined the validity by measuring T_{min} only with considerably low speed. Future investigations should examine to what extent of speed these assumptions are applicable. We simply assumed that T_{const} denotes temporal processing and is related to stimulus pattern processing. However, the process involved in T_{const} is still not known clearly, as mentioned above. This should also be cleared up in future investigations.

Moreover, the present study used plaids as stimuli. Plaids are made of component sinusoidal gratings which are thought to be detected independently by separate classes of motion selective cells from the cells responding to the pattern motion (e.g., Movshon, Adelson, Gizzi, & Newsome, 1986). Therefore, deliberate researchers may avoid using plaids as stimuli on the studies about judgements of motion direction and use the random dot pattern (RDP). We assume that there is no difference between plaid and RDP because observers would use only the activity of horizontal motion detectors on the task. However, this should be confirmed by the future investigations.

The present study measured T_{min} only in foveal vision conditions (i.e., eccentricity was not considered) without a reference stimulus. We used small red dots for indicating the approximate position of stimuli. These might play a role of framework to a certain extent but are different from fixation points (see Figure 1a). If T_{min} were measured using higher speed and peripheral conditions with a fixation point as the reference stimulus, the values might be greatly different from those obtained here. Further investigations will be also required to examine these conditions.

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