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Modification of saccade-contingent visual mislocalization by the presence of a visual frame of reference

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Abstract

The effect of three kinds of background visual field on saccade-contingent mislocalization was compared so as to explore the critical factor responsible for visual stability during saccadic eye movements. A large mislocalization observed in the dark (DARK condition) was substantially decreased when a faint frame pattern was projected against the dark background (FRAME condition) as well as when the background screen being illuminated (LIGHT condition). Large mislocalization in the DARK condition occurred both when targets were presented just before the beginning of a saccade and when they were presented at the end of the saccade, irrespective of the position at which the target was presented. In contrast, in the FRAME and LIGHT conditions, mislocalization appeared to depend on target position. Mislocalization of targets presented immediately before the saccade onset diminished when they were presented near the saccade goal, whereas mislocalization of targets presented at the end of the saccade diminished when they were presented near the original fixation point. It was concluded from these results that the subject made use of the frame and the illuminated background as a visual cue for exocentric localization of the target, and that a saccade-contingent shift of visual attention was involved in producing the selective diminution of mislocalization observed in FRAME and LIGHT conditions. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Saccade; Visual localization; Visual stability; Eye position signal

1. Introduction

A visual stimulus flashed in the dark near the time of a saccadic eye movement is perceived at a different position from its actual position (Matin, Matin & Pearce, 1969; Matin, Matin, Pola & Kowal, 1969; Matin, Matin & Pola, 1970; Matin, 1976; Kennard, Hartman, Kraft & Glaser, 1971; Honda, 1990, 1991, 1997). This visual mislocalization occurs when stimuli are presented in the time span from about 100 ms before to 100 ms after movement onset. The direction of mislocalization is dependent on the timing of the stimulus presentation relative to the saccade onset. When stimuli are presented immediately before or at the beginning of a saccade, mislocalization occurs in the same direction as the saccade, whereas when stimuli are presented immediately after the saccade offset, they are mislocalized in the direction opposite to the saccade. Dassonville, Schlag and Schlag-Rey (1992) found approximately the same mislocalization in an oculomotor localization task.

A similar mislocalization has been reported for a visual stimulus presented on a visible background (Bischof & Kramer, 1968; Honda, 1993; Mateeff, 1978; O'Regan, 1984). However, the magnitude of mislocalization shown in the 'visible background' condition is small in comparison with that shown in the dark. In the study by Honda (1993), for example, the range of mislocalization observed in the total darkness was nearly comparable to the saccade size, but it became less than half of the saccade size when stimuli were presented on a dimly illuminated structured background.

The predominant theory for explaining the saccade-contingent mislocalization is the cancellation theory (von Helmholtz, 1866). This theory explains that visual information about image displacement produced by a saccade (retinal signal, RS) is compared with an internal signal about eye movements (extraretinal eye position signal, EEPS), and that a mismatch is generally perceived as movements of the object in the world. According to this theory, the mislocalization observed

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in the dark is predominantly produced by a mismatch between the EEPS and the retinal signal. In contrast, the mechanism responsible for generating the decreased mislocalization in the visible background condition seems more complicated (Matin, 1986; Skavenski, 1990). The most convincing explanation is that, in the visible background condition, the subject can make use of many visual cues for judging the stimulus position. For example, the subject may judge the stimulus position in relation to the edge of the illuminated background screen. This explanation seems plausible, because some previous studies have demonstrated that mislocalization is significantly influenced by presenting a non-target visual stimulus against the dark background. Matin, E. et al. (1969), for example, showed that mislocalization rapidly disappeared immediately after the end of a saccade when a very small light spot was continuously presented just above the original fixation point. Similarly, Dassonville, Schlag and Schlag-Rey, (1995) found that saccadic oculomotor localization became more accurate when the saccade goal stimulus was continuously presented until the presentation of a target stimulus.

The present study was conducted to establish how the saccade-contingent mislocalization is modified by changing the structure of the background visual scene. For this purpose, subjects judged the position of a visual stimulus flashed near the time of a saccade in two kinds of visible background conditions, LIGHT and FRAME, and compared the results with those obtained when the stimulus was presented in the total darkness (DARK condition). In the LIGHT and FRAME conditions, stimuli were presented on a dimly illuminated background or within a bright rectangular visual frame drawn against a dark background, respectively. By comparing the results in these three background conditions, an attempt is made to clarify the critical determinants of visual mislocalization associated with saccadic eye movements.

2. Method

Subjects were seated in the dark with the head fixed by a chin- and forehead-rest. Horizontal eye movements of each subject's right eye were measured by a photoelectric limbus tracking method with an accuracy of more than 0.5°, and recorded by a digital data recorder (TEAC, DR-F1) with a sampling rate of 500 Hz. Subject's eye movements were later analyzed by a high-speed digital storage scope (Iwatsu, DS-6121A). Eye position data were used to establish the timing of target stimulus presentation, to obtain measures of saccade and to examine drift before and after saccade.

A rear-projection screen (25° in height and 55° in width) was placed 57 cm from the subject's eye. The center of the screen was located straight ahead positioned exactly between the two eyes. On each trial, a buzzer warning signal was given, and then a fixation point (a red rectangular LED, 0.3° in height and 0.2° in width, 25 cd/m^2) was presented 4° left of the center of the screen. The duration of the fixation point varied from trial to trial between 1 and 2 s. When the fixation point was turned off, a visual stimulus for eliciting a saccade (a red rectangular LED, 0.6° in height and 0.2° in width, 30 cd/m^2) was presented for 20 ms, 8° right of the fixation point. The subject made an 8° horizontal saccade toward the saccade goal. At a varying point in time before, during or after the saccade, a target stimulus (a red LED, 0.5° in diameter, 40 cd/m^2) for localization was presented for 2 ms. The target was presented at one of the three target positions: (1) near the original fixation point, i.e. 2° left of the fixation point; (2) exactly between the fixation point and the saccade goal, i.e. at the center of the visual field; (3) near the saccade goal, i.e. 2° right of the saccade goal. After the completion of the primary saccade, the subject usually directed his gaze toward the position the target was seen (Fig. 1). About 1.4 s after disappearance of the target, a probe stimulus (a yellow LED, 0.5° in diameter, 20 cd/m^2) was presented for 5 s at a position just above the row of target LEDs. The subject could move the horizontal position of the probe stimulus by turning a knob with the right hand, and indicated the apparent position of the target. In reality, all LEDs were set on a blackboard placed at a different position from the screen. The subject saw the LEDs through a half-silvered mirror set before the subject's eye. By this, these visual stimuli were presented as an optical image against the background screen.

The experiment was conducted in three background conditions. In the DARK condition, the experiment was carried out in the dark. In the LIGHT condition, the screen was dimly illuminated from the back by a slide projector. The average luminance level of the screen was 15 cd/m^2. In the FRAME condition, a rectangular visual frame was rear-projected at the center of the dark screen. The frame consisted of thin bright lines (0.5° in width, 15 cd/m^2). The height and the width of the inner contour of the frame were 5.5° and 18°, respectively. As shown in Fig. 2, the distance between the fixation point and the inner contour of the left side of the frame was 5°. Similarly, the saccade goal was placed 5° left of the right side of the frame.

The author and two male university students with no experience in eye-movement experiments participated in this experiment. Each subject took part in the experiment for 9 days. On each day, the subject participated in eight experimental sessions, 16 trials in each session, total of 128 experimental trials. The first four sessions were conducted in one of the three background conditions (e.g. the DARK condition), and the last four

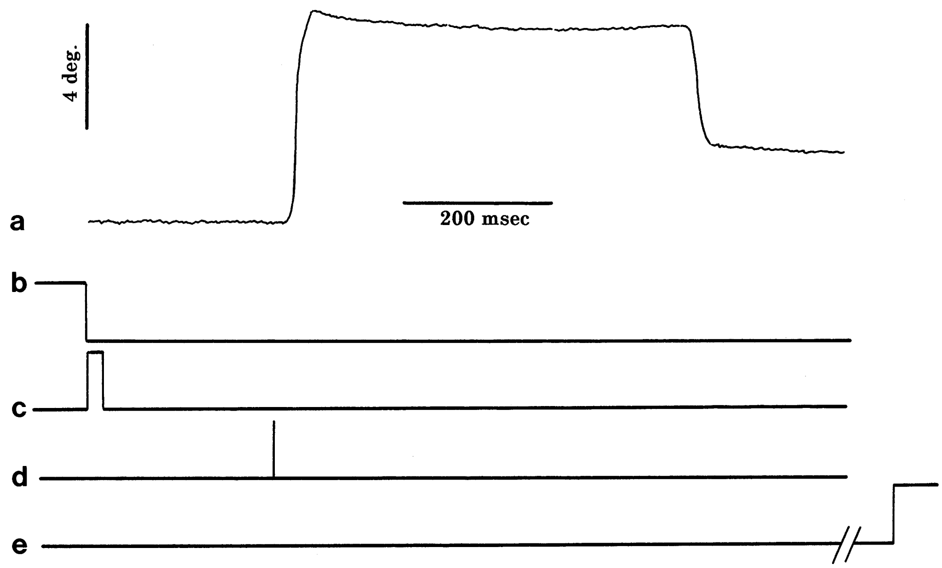

Fig. 1. A typical record of horizontal eye movements and the chronology of events comprising the stimulus presentation (subject MH); a, eye movements; b, fixation point; c, saccade goal; d, target; e, probe stimulus. In this case, the target was presented just before the saccade onset, exactly between the fixation point and the saccade goal on an illuminated background (LIGHT condition).

sessions were selected from the remaining two conditions (e.g. the LIGHT or FRAME condition). The combination of the two background conditions employed in each day varied from day to day, resulting in total of 24 sessions per background condition, counterbalanced within the 9 days.

In addition to the experimental sessions, two control sessions of nine trials each were conducted to examine how accurately the subject could localize the target when he was not required to make a saccade. The first control session was inserted between the fourth and fifth experimental sessions, and the second control session was conducted after the last experimental session.

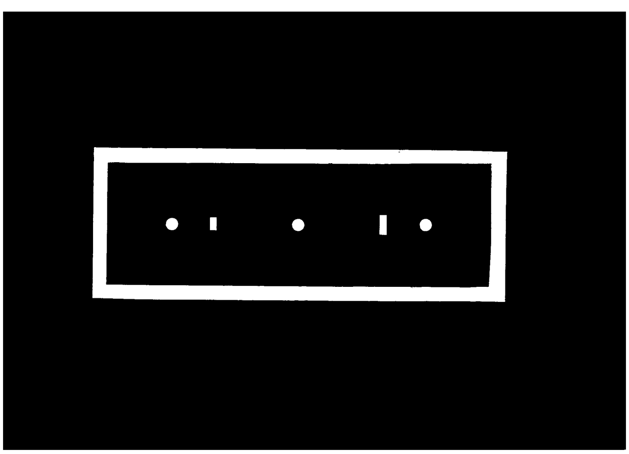

Fig. 2. Arrangement of the fixation point (left small rectangular), the visual cue for a saccade (right small rectangular) and three target positions (small disks) in the FRAME condition. A probe stimulus was presented somewhere 0.5° above the row of three possible positions of visual target.

On the control trial, either the fixation point or the saccade goal was presented for 2 s, and the subject was asked to fixate these stimuli. Immediately after the offset of these stimuli, a target was presented for 2 ms, and the subject indicated its apparent position in the same way as the experimental trials.

In some experimental trials, the latency of the saccade was extremely short (<80 ms) or long (>400 ms). The data obtained from these trials were not used in the following data analysis. If the eye movement recording was contaminated with an eye blinking or a large drift more than 1°, the data from these trials were excluded from the data analysis. As a result, about 9% of the experimental trials were rejected.

3. Results

3.1. Eye movements

In 38%of experimental trials, a small drift of the eye was observed at the interval between the extinction of the fixation point and the beginning of a saccade. In many cases (about 80%), it occurred in the direction opposite to the saccade, and its amplitude was less than 0.5°. Drift of the eye also occurred after the saccade completion (see Fig. 1). This post-saccadic drift was always toward the fixation point, and interrupted by the second saccade made to the apparent position of a target. These involuntary pre- and post-saccadic drifts were observed equally in every background condition, and could not therefore be responsible for the results and the conclusion of this study.

Table 1
Means and S.D.s (in brackets) of amplitude, duration and latency of the primary saccades in the three background conditions

Subject	Condition	Amplitude (°)	Duration (ms)	Latency (ms)
HH	DARK	8.2 (1.2)	34.0 (4.0)	168.2 (20.3)
	LIGHT	8.5 (1.1)	33.0 (3.6)	179.1 (24.1)
	FRAME	8.6 (1.3)	32.4 (4.0)	179.0 (27.8)
IK	DARK	7.9 (0.9)	41.4 (4.4)	174.1 (32.7)
	LIGHT	7.9 (1.1)	42.0 (4.6)	187.5 (44.0)
	FRAME	8.0 (1.3)	44.8 (5.6)	170.2 (44.7)
HM	DARK	7.8 (1.0)	35.6 (4.1)	216.3 (67.6)
	LIGHT	7.6 (0.9)	35.1 (2.5)	192.1 (46.4)
	FRAME	7.6 (1.1)	33.9 (3.2)	192.5 (46.0)

In 22% of control trials, a small drift of the eye was observed after the extinction of the fixation point, but its amplitude never reached 0.5° and its direction was not consistent. Therefore, it is evident that the small drift observed in some control trials did not have any significant effect on visual localization.

As shown in Table 1, there was a small but significant difference in the saccade amplitude between the three subjects ($F(2, 3124) = 112.3$; $P < 0.01$). Subject HH slightly overshot the saccade goal ($t = 11.47$; $df = 1024$; $P < 0.01$), whereas subject HM's saccades were slightly shorter than the expected amplitude of 8° ($t = 11.30$; $df = 1075$; $P < 0.01$). For each subject, however, no significant difference was observed in the saccade amplitude between the three background conditions. There was also a significant between-subject difference in both the duration ($F(2, 3124) = 1584.5$; $P < 0.01$) and the latency ($F(2, 3124) = 48.4$; $P < 0.01$) of the saccades. In addition, for all subjects, the average latency was different between the three background conditions ($P < 0.01$ for each subject). One possible reason for this difference in saccade latencies between the three background conditions is that the three background conditions were not randomized within each experimental session. As described below, however, these parameters of the initial saccade did not have any substantial effect on the subjects' visual localization performance.

3.2. Visual localization

All subjects showed a small mislocalization in the control trials in which they did not make a saccade. The mean of the absolute value of these indigenous errors was 0.5° (S.D. = 0.35). Before analyzing the saccade-contingent mislocalization, a data correction was made using the response bias shown in the control trials. That is, when a target was presented before the beginning of a saccade, the mislocalization error was corrected by using the mean error shown in the control trials in which the subject was asked to keep watching the fixation point. On the other hand, when a target was presented after the end of a saccade, the mean error shown when the subject was asked to keep watching the saccade goal was used. Finally, for correcting the mislocalization of a target presented during a saccade, the mean of the errors obtained in the two kinds of control trials was used.

Fig. 3 shows the saccade-contingent mislocalization in the three background conditions as a function of the timing of target presentation with respect to the beginning of a saccade, separately for the three target positions. The symbols ●, ■ and ◆ in Fig. 3 represent the three subjects HH, IK and HM, respectively. The timing of target presentation was manipulated by varying the time interval between the offset of the saccade goal and the onset of the target, randomly, from trial-to-trial. Because of this, it was impossible to obtain a fixed number of data points at a given timing of target presentation. In calculating the mean error, therefore, the width of bins on the abscissa was determined so that at least five samples were included within each bin, with the result that the number of means, as well as the width of each bin, was uneven between the three background conditions in each subject. For this reason, an ordinary multiple-factor statistical analysis was not applicable to the present data. Instead, the effect of timing of target presentation for each target position in each background condition was analyzed separately for each subject, using a 1-factor ANOVA and subsequent post hoc multiple component analyses (Scheffe's procedure).

As shown in Fig. 3, a large mislocalization was observed in the DARK condition. When a target was presented before or at the beginning of a saccade, all subjects mislocalized the target in the same direction as the saccade. This pre-saccadic mislocalization occurred about 50 ms before the saccade and reached maximum at the beginning of the saccade. In contrast, for a target presented at the end of a saccade, a large mislocalization in the direction opposite to the saccade was observed. This post-saccadic mislocalization was observed until about 50 ms after the end of the saccade. The range of mislocalization, i.e. the peak-to-peak amplitude of the error curve, was about three fourths or more of the saccade amplitude. In addition, the time course of mislocalization, i.e. the effect of timing of target presentation, was about the same between the three target positions.

In the LIGHT and FRAME conditions, mislocalization was reduced. Fig. 4 shows the range of mislocalization shown in the three background conditions. According to statistical analysis, the effect of background condition was significant ($F(2, 4) = 32.23$, $P < 0.01$), but the difference between the three target positions was not significant. Subsequent multiple comparisons using Scheffe's procedure showed that the mislocalization in the DARK condition was signifi-

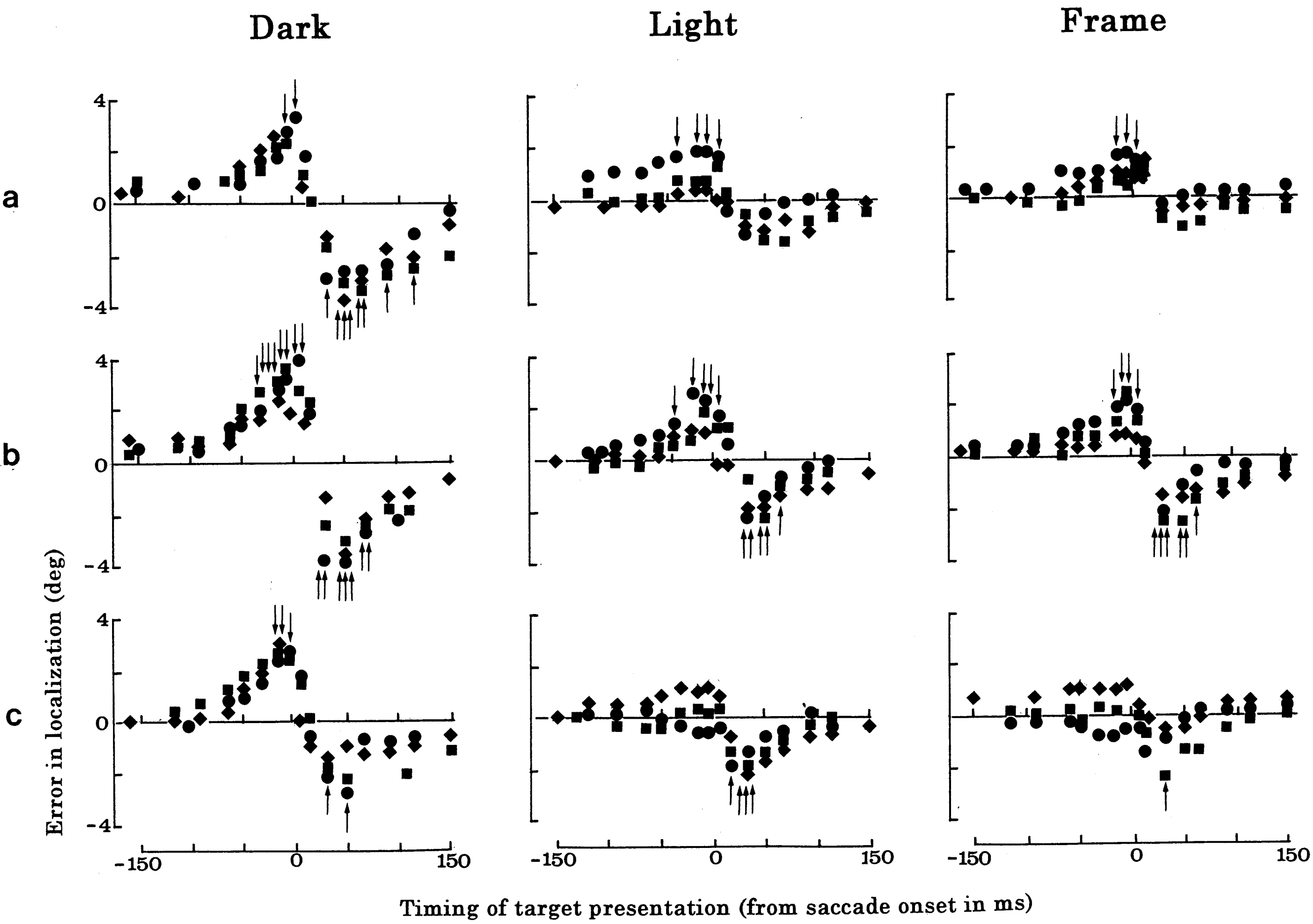

Fig. 3. Visual mislocalization in the three background conditions as a function of the timing of target presentation with respect to the onset of the initial saccade (at 0 ms on the abscissa; negative numbers indicate before saccade onset, positive numbers indicate after saccade onset). ●, subject HH; ■, subject IK; ◆, subject MH; a, mislocalization when a target was presented near the original fixation point; b, mislocalization when a target was presented exactly between the fixation point and the saccade goal; c, mislocalization when a target was presented near the saccade goal. A plus sign (+) in the ordinate shows mislocalization in the saccade direction. Each symbol is the average of 5–25 trials. Arrows indicate that the mislocalization represented by the symbol was significantly different from that in control trials (0 in the ordinate).

cantly larger than that in the LIGHT and FRAME conditions ($P < 0.05$).

Another important observation is that in both the LIGHT and FRAME conditions there was a substantial difference in the effect of timing of target presentation between the three target positions. That is, when a target was presented near the original fixation point, the post-saccadic mislocalization in the direction opposite to the saccade became smaller or disappeared, but the pre-saccadic mislocalization in the saccade direction remained salient (arrows in Fig. 3). On the other hand, when a target was presented near the saccade goal, pre-saccadic mislocalization in the saccade direction became smaller or diminished.

4. Discussion

The present study indicated that saccade-contingent mislocalizations in the LIGHT and FRAME conditions were approximately the same. That is, (1) mislocalization in these two conditions was smaller than that in the DARK condition, and (2) although a strict statistical analysis was impossible, in the LIGHT and FRAME conditions the time course of mislocalization appeared changed depending on the position at which the target was presented.

It is evident, therefore, that the overall illumination level of the background was not important, because in the FRAME condition almost all of the visual field except the frame pattern was perfectly dark. What was common to the two visible background conditions was that there existed a visual frame of reference for judging the exocentric position of a target. That is, in the LIGHT condition, the subject was able to judge the target position in relation to the edge of the illuminated screen, resulting in the same localization accuracy as that in the FRAME condition. This explains why the mislocalization in the two conditions was smaller than that in the DARK condition, which is consistent with earlier studies showing that mislocalization is greatly influenced by the existence of a non-target stimulus on the dark background (Dassonville et al., 1995; 1995; Matin, E. et al., 1969; Matin, Picoult, Stevens, Edwards, Young & MacArthur, 1980). Dassonville et al. (1995) interpreted their results as showing that the continuously presented saccade goal served as an exocentric localization cue. However, it is important to note here that in the FRAME and LIGHT conditions mislocalization did not completely disappear. This suggests that the visible background used here did not provide a sufficient visual cue for exocentric localization. Another reason may be that, in everyday life in which visual stability is observed, objects never visually appear as flashes.

The next question is why the time course of mislocalization in the LIGHT and FRAME conditions appeared changed depending on the position at which a target was presented. At present, it is difficult to fully explain this observation. However, a part of this finding may be explained by assuming some kinds of attention processes. As shown in Fig. 3, in these two conditions, pre-saccadic mislocalization in the saccade direction decreased when a target was presented near the saccade goal. One possible reason for this is that a saccade caused a rapid shift of visual attention to the position near the saccade goal. This shift of attention occurs before the saccade onset (Remington, 1980; Shepherd, Findlay & Hockey, 1986). A related finding was reported by Duhamel, Colby & Goldberg (1992). They showed that when a monkey was required to make a saccade, a receptive field of some parietal neurons shifted transiently in the saccade direction before the eye began to move. These findings suggest that when a subject was required to make a saccade, a selective facilitation of exocentric localization processing occurred at the visual field near the saccade goal, resulting in a decreased mislocalization. After the saccade, however, a substantial mislocalization appeared. This can be explained by assuming that visual attention shifted to on other area in the visual field ('inhibition of return' phenomenon, Posner and Cohen, 1984; Mayor & Hockey, 1985).

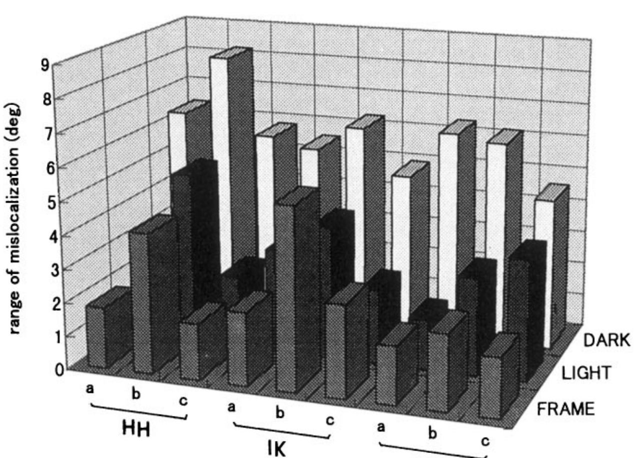

Fig. 4. Comparison of the range of mislocalization (the peak-to-peak amplitude of the mislocalization curve) in the three background conditions. a, b and c indicate the three target positions, i.e. a, near the fixation point; b, between the fixation point and the saccade goal; c, near the saccade goal.

When a target was presented near the fixation point, mislocalization became smaller especially when the target was presented immediately after the end of a saccade (upper data in Fig. 3). This diminution of post-saccadic mislocalization may be explained by assuming that visual attention went back from the saccade goal to the area around the fixation point.

Needless to say, the explanation proposed here is not complete. For example, it is not clear how facilitation of visual processing makes the mislocalization associated with a saccade smaller. In addition, there is no established evidence that visual attention tends to return to the original fixation point after the completion of a saccade. Further investigation would be needed for these matters. Finally it should be noted here again that in the present study no direct statistical analysis was applicable to test the effects of background condition (DARK/LIGHT/FRAME in Fig. 3) and target position (a, b, c in Fig. 3) and their interaction. This may weaken the conclusions of this study. However, I believe that the findings reported in this study are not artifact but provide useful information for explaining the long-standing problems on how we localize targets while the eye is in motion.

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