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Apparent size of an object remains uncompressed during presaccadic compression of visual space

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Abstract

It is well known that compression of visual space occurs near the saccade goal when visual stimuli are briefly flashed at various locations on a visual reference just before a saccade. We investigated how presaccadic compression of visual space affected the apparent size of an object. In the first experiment, subjects were instructed to report the apparent number of multiple bars briefly presented around the time of saccade onset. The reported number of four bars began to decline at the 50 ms mark before a saccade and reached a minimum near the saccade onset. This confirms that the compression of visual space occurs just before saccades. In the second experiment, subjects judged the apparent width of a rectangle (a single element) or four bars (four elements) presented just before saccades. The apparent width of the four-bar stimulus was compressed just before saccades, but that of the rectangle stimulus was not compressed. Experiment 3 shows that the width compression of the four-bar stimulus is consistent with the width change predicted by compression of position. These findings indicate that the shape of a single object is not distorted at the saccade goal during presaccadic compression of visual space. In addition, experiment 4 indicates that the apparent width of a flashed stimulus just before saccades depends on the processing of global shape. This extends the definition of a visual object during presaccadic compression of visual space to not only a solid element but also a constellation of multiple elements. Furthermore, the results from these experiments suggest that presaccadic compression of visual space does not prevent object recognition underlying an attentional mechanism in generating saccadic eye movements.

Keywords: Saccade; Visual space; Size discrimination; Localization; Visual attention

1. Introduction

When a stimulus is flashed in the dark during a saccadic eye movement, the stimulus is mislocalized in the direction of the saccade (Matin, Matin, & Pearce, 1969; Honda, 1990, 1991; Dassonville, Schlag, and Schlag-Rey, 1995; Schlag & Schlag-Rey, 1995). This mislocalization starts increasing about 100 ms before the saccade and reaches a maximum at the saccade onset. The direction of the mislocalization is uniform across the visual field (Honda, 1991; Dassonville et al., 1995). However, when a stimulus is flashed on a visual reference during a saccade, the direction of the mislocalization is non-uniform across the visual field (Bischof & Kramer, 1968; O'Regan, 1984; Honda, 1993, 1995, 1999; Dassonville et al., 1995; Morrone, Ross, and Burr, 1997; Ross, Morrone, & Burr, 1997; Lappe, Awater, & Krekelberg, 2000). In the investigation by Ross et al. (1997), for example, a stimulus flashed between the fixation point and the saccade goal was mislocalized in the direction of the saccade, and a stimulus flashed beyond the saccade goal was mislocalized against the direction of the saccade. These mislocalizations were found within the period of − 50 ms to about 50 ms relative to the saccade onset. Thus, the results show that stimuli flashed at various locations are mislocalized towards the saccade goal when a visual reference is presented.

In addition, Morrone et al. (1997) and Ross et al. (1997)asked subjects to report the apparent number of

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multiple bars presented briefly at surrounding locations of a saccade target during a saccade. They found that the apparent number of multiple bars decreased near the saccade onset, and the time course of the apparent number of bars relative to the saccade onset corresponded to that of the mislocalization. Therefore, they concluded that the compression of visual space occurred at the saccade goal just before saccades.

What aspect of the visual stimuli provided by the multiple bars is compressed during compression of visual space just before saccades? When multiple bars are briefly presented just before a saccade, the visual system may regard the multiple bars as separate multiple objects. As a result, the location of each object may be compressed in the visual space. If this were true, one would predict that less compression occurred when a non-separate single object was briefly presented at the saccade goal just before the saccade. Consequently, the deformation of the object image may occur less. The present study was conducted to investigate how presaccadic compression of visual space affected the perceived shape of an object at the saccade goal. Experiment 1 was designed to confirm the results of Morrone et al. (1997) and Ross et al. (1997). Subjects judged the apparent number of multiple bars flashed during a saccade. In experiment 2, we compared the apparent width of a flashed rectangle presented just before a saccade with that of flashed four bars presented just before a saccade. In experiment 3, we measured the apparent position of a flashed bar presented at the positions of the left and right edges of the rectangle. This gave an estimate of the width change of the rectangle predicted by presaccadic compression of visual space. In experiment 4, we measured the apparent widths of an outline rectangle made of dots, outline three-bars made of dots, and a solid rectangle presented just before a saccade. This indicated what was the crucial difference between the compressed and uncompressed stimuli during presaccadic compression of visual space.

2. General methods

2.1. Apparatus

Subjects sat in the dark for 3 min before beginning the experiment. Each subject's head was fixed with a combination of bite bar and forehead rest at 25 cm from the display. Visual stimuli were presented on a CRT display, which had a refresh rate of 60 Hz (Sony GDM-2000TC) in experiments 1 and 2, and that of 67 Hz (Sony SUPERMATCH 20-T) in the part of experiment 2 and in experiments 3 and 4. The display subtended 59 deg height and 74 deg wide was computer-controlled (Apple Power Macintosh 7100/66AV in experiments 1 and 2; Apple Macintosh Quadra 950 in the part of experiment 2 and in experiments 3 and 4).

A limbus tracking device, which consisted of two infrared emitting diodes and two photo diodes, measured the horizontal eye movement of each subject's left eye with an accuracy of about 0.1 deg. To acquire eye position, we subtracted the output voltage of one photo diode from that of the other photo diode and amplified the voltage subtracted from the two photo diodes. The eye position data were recorded by the computer via an A/D converter (MacADIOS II in experiments 1 and 2; National Instruments NB-MIO-16H in the part of experiment 2 and in experiments 3 and 4). The eye position data were acquired with a sampling rate of 60 Hz in experiments 1 and 2. In the part of experiment 2 and in experiments 3 and 4, the sampling rate was 67 Hz. We differentiated the eye position to obtain eye velocity. A saccadic latency was defined as a period until an eye velocity exceeded 30 deg/s after a flashed saccade target. The onset of a saccade triggered the visual stimuli presentation in experiments 1 and 3.

2.2. Calibration of eye movement

Each trial started with a calibration procedure as follows: a subject had to sequentially fixate five dots presented in sequence on a horizontal line of the display center. After the subject fixated the dot, the subject pushed a button. That dot disappeared, and the next one appeared. The horizontal eye positions, which were expressed by voltage, and the dot positions on the screen were recorded in the computer. A regression line was used to convert the voltage to the dot position.

3. Experiment 1: Apparent number of multiple bars during saccades

Experiment 1 was conducted to confirm compression of visual space just before saccades. Multiple bars ranging between one and four bars were briefly presented around the saccade goal at variable times before, during, or after a saccade. Subjects reported the apparent number of the multiple bars.

3.1. Stimuli

Fig. 1 shows the configuration of stimuli. The luminance of a background on the screen was 2.0 cd/m^2. Fixation and saccade cues (two red rectangles in the left and right sides of the screen; each rectangle was 0.5 deg in height and 2.0 deg in width, 15 cd/m^2) were presented at -10 and 10 deg horizontally from the display center, respectively. Multiple bars (each bar was 10 deg in height and 1.4 deg in width, 15 cd/m^2) were flashed for 16.7 ms at some or all of four possible positions (5, 8, 12, and 15 deg from the display center) around the saccade cue. The number of bars, the positions where the bars were presented, and their delay were varied at random from trial to trial. The four bars were presented more frequently than the other cases of one, two, or three bars. As shown in Fig. 1, the ruler (15 cd/m^2) served as a visual reference.

3.2. Procedure

Each subject fixated the center of the fixation cue presented at −10 deg from the display center. Then, the subject pressed a button. After a delay selected randomly between 500 and 1000 ms, the fixation cue was extinguished and replaced by the saccade cue. The saccade cue was presented for 50 ms at 10 deg from the display center. Subject made a 20 deg rightward horizontal saccade towards the saccade cue. After a randomly selected delay from saccade onset time (−100 to +100 ms), multiple bars (between 1 and 4) were presented for 16.7 ms about the saccade goal. If the delay from saccade onset was selected between −100 and 0 ms, the presentation time of the multiple bars was decided using the saccade onset, which was predicted from the average saccadic latency of the previous four trials. If the delay from saccade onset was selected between 16.7 and 100 ms, the presentation time of the multiple bars was decided using the actual saccade onset. By means of the subsequent data analysis, the delays between −100 and 0 ms were transformed to delays from the actual saccade onsets. After the saccade, the subject reported how many bars he saw. Each subject performed five sessions; a session consisted of 104 trials (four bars: 65 trials; three bars: 13 trials; two bars: 13 trials; one bar: 13 trials).

In control trials, the same sequence of visual stimuli as the saccade trials was displayed, and the subject was instructed to keep fixating at −10 or +10 deg from the screen center. Each subject performed four sessions. When a saccade occurred in a control trial, the trial was cancelled and again repeated at another opportunity in the session.

3.3. Subjects

Three male subjects (KM, 28 years old, HM, 24 years old, and HA, 22 years old) participated in the experiment. All subjects had normal vision. Subject KM was one of the authors. Subject HM was experienced in a variety of experiments related to saccadic eye movement study. Subject HA was naïve in the experiment of saccadic eye movement study.

3.4. Results and discussion

Fig. 2 shows the apparent number of multiple bars as a function of time from saccade onset for three subjects. The four graphs in each row of Fig. 2 represent the number of bars presented on the screen. The dots

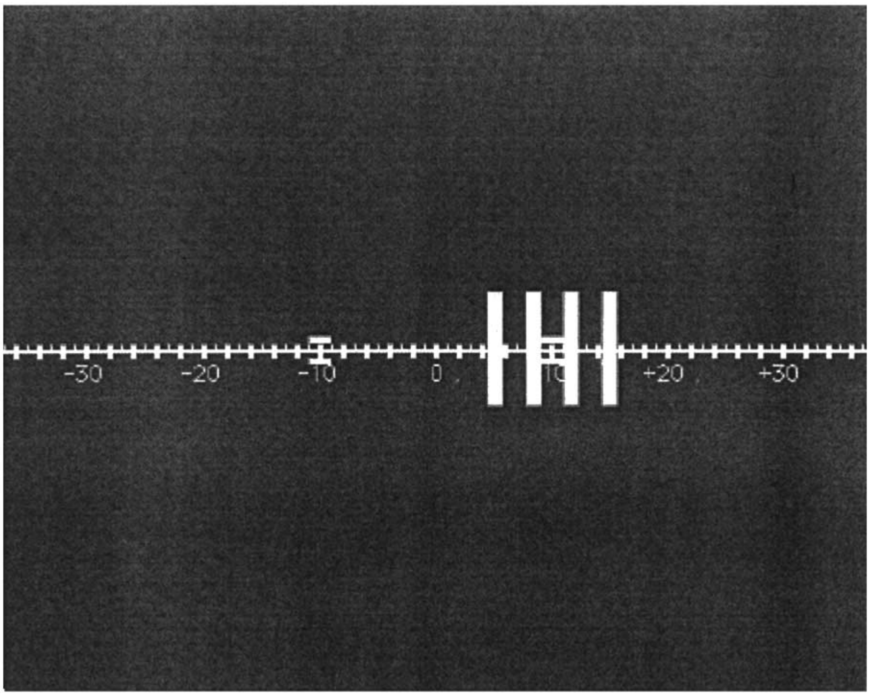

Fig. 1. Arrangement of the horizontal ruler, the visual cues for a fixation (left two rectangles) and a saccade (right two rectangles), and the four bars in experiment 1.

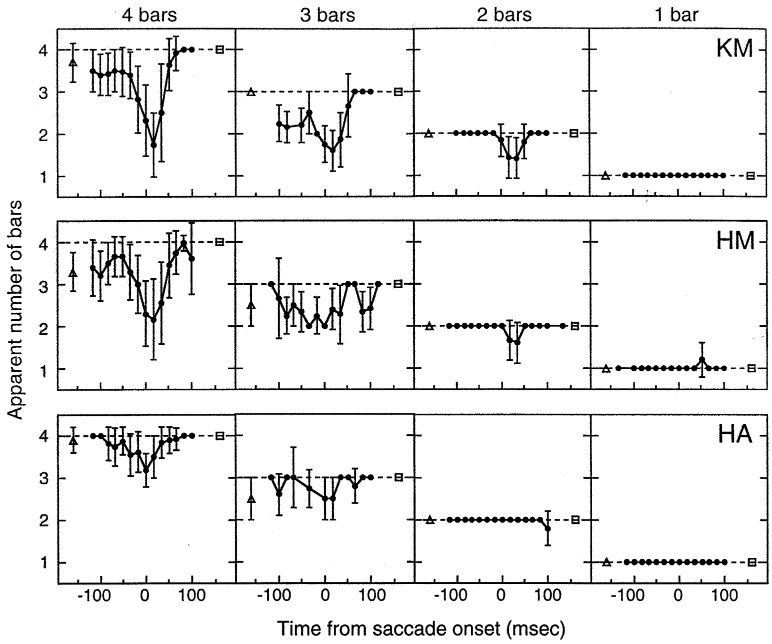

Fig. 2. Apparent number of four bars, three bars, two bars, and one bar as a function of time from saccade onset. The top, middle, and bottom panels represent subjects KM, HM, and HA, respectively. Dashed lines represent the number of bars presented on a screen. Solid circles: saccade condition; open triangles and squares: fixation condition. The open triangles and squares represent the results in the cases that subjects fixated 10 deg left and right from the center of the screen, respectively. The four bars were presented more frequently than the other cases of one, two, or three bars.

indicate the results of the saccade trials. The open triangles and squares demonstrate the control trials in which the subjects kept fixating at −10 and +10 deg from the display center, respectively.

When four or three bars were presented within the range of −50 to 75 ms relative to the saccade onset, all subjects tended to underestimate the number of bars. These results agreed with those obtained by Morrone et al. (1997) and Ross et al. (1997). For subjects KM and HM, the underestimation of the number of bars tended to occur when four, three, or two bars were presented within the critical period. For subject HA, the underestimation tended to be smaller than the other subjects and no longer occurred, even though two bars were presented within the critical period. Well before the saccade (−50 ms and under), subjects KM and HM, except subject HA, tended to slightly underestimate the number of bars for the presentation of four or three bars, but they reported correctly the number of bars for the presentation of two bars or one bar. Subject HA tended to report the same number as the presented bars well before the saccade. These results had the same tendencies as the results obtained during fixation at −10 deg from the display center. After the saccade (75 ms and over), all subjects tended to report the same number as the presented bars. This tendency was the same as the results obtained during fixation at 10 deg from the display center. Thus, these results indicate that compression of visual space occurs within the critical period between −50 and 75 ms relative to saccade onset.

4. Experiment 2: Size discrimination for single-rectangle and multiple-bars just before saccades

In experiment 2, we examined whether the width of the rectangle consisting of a single element was compressed during presaccadic compression of visual space. Subjects compared the width of a visual stimulus presented briefly just before a saccade with that during fixation in each condition of the rectangle and the four bars.

4.1. Stimuli

As shown in Fig. 3, rectangle and four-bar stimuli were flashed at the location of the saccade goal in the rectangle and four-bar conditions, respectively. The two types of reference stimuli were used in each condition. A large reference stimulus subtended 10.0 deg in height and 15.0 deg in width, and a small reference stimulus subtended 10.0 deg in height and 11.4 deg in width. The six types of test stimuli were used in each case of the large and small reference stimuli.

In the rectangle condition, the width of the test stimulus was randomly chosen from '11.0, 13.0, 14.4, 15.6, 17.0, and 19.0 deg' and '7.4, 9.4, 10.8, 12.0, 13.4, and 15.4 deg' in the case of the 'large' and 'small' reference stimuli, respectively. These widths were used in both the saccade and fixation conditions. In the four-bar condition, the range of the width of the test stimulus was different between the saccade and fixation conditions. In the saccade condition, the width was selected at random from '13.0, 14.4, 15.6, 17.0, 19.0, and 21.0 deg' and '9.4, 10.8, 12.0, 13.4, 15.4, and 17.4 deg' in the case of the 'large' and 'small' reference stimuli, respectively. In the fixation condition, the width was selected at random from the same range as the rectangle condition. All types of test stimuli had 10.0 deg in height. The luminances of both reference and test stimuli were 15 cd/m^2. The other stimuli were identical to those used in experiment 1.

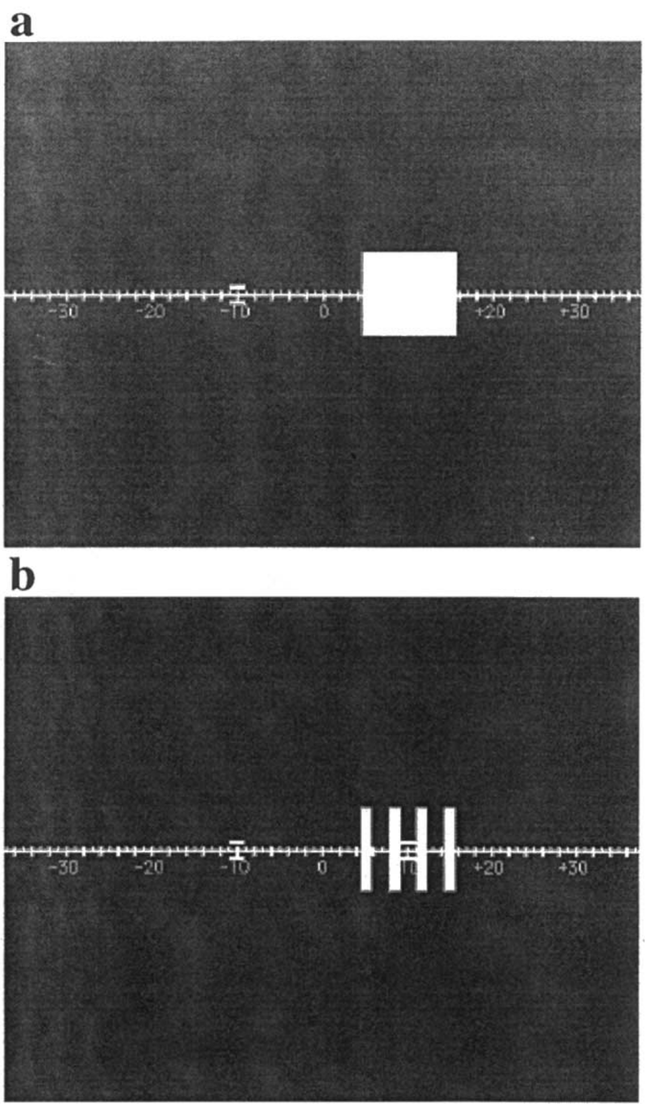

Fig. 3. Arrangement of visual stimuli in experiment 2; (a), the rectangle condition; (b), the four-bar condition.

4.2. Procedure

Each subject fixated the center of the visual cue presented at −10 deg from the display center. Then, the subject pressed a button. After a delay selected randomly between 500 and 1000 ms, the fixation cue was extinguished and replaced by the saccade cue presented for 50 ms at 10 deg from the display center. The subject made a 20 deg rightward horizontal saccade towards the center of the saccade cue as soon as possible. The saccade onset time was predicted from the average saccadic latency of the previous four trials. One video frame before the predicted saccade onset, a test stimulus was presented for one video frame around the saccade goal. The test stimulus was randomly selected among the 12 types (large: six types, small: six types) of test stimuli. After a delay of 700 ms, the fixation cue was presented again, and the subject repeated the similar procedure described above except to keep fixating at −10 deg from the display center. Two hundred milliseconds after the saccade cue was extinguished, a reference stimulus was presented for one video frame around the saccade goal. Either a 'large' or a 'small' reference stimulus was selected depending on the random selection of the test stimulus. Finally, the subject reported which width was larger, the test or reference stimuli. The same procedure described above was used in both the rectangle and four-bar conditions. Each condition was conducted in separate sessions. Each subject performed 12 sessions; a session consisted of 84 trials. Trials were excluded from the data analysis if the test stimulus was not presented between −33.4 and 0 ms relative to the actual saccade onset. The one video frame was 16.7 ms for subjects KM and HM, and 15.0 ms for SM. This is because the type of CRT displays was different.

In control trials, the same sequence of visual stimuli described above was presented while the subject maintained their fixation at −10 deg from the display center when either the test or reference stimulus was presented. Each subject performed 12 sessions; a session consisted of 84 trials. When a saccade occurred in a control trial, the trial was cancelled and again repeated at another opportunity in the session.

4.3. Subjects

Three subjects two male and one female (KM, 28 years old, HM, 24 years old, and SM, 29 years old) participated in experiment 2. Subjects KM and HM were the same subjects as experiment 1. Subject SM was naïve in the experiment of saccadic eye movement study.

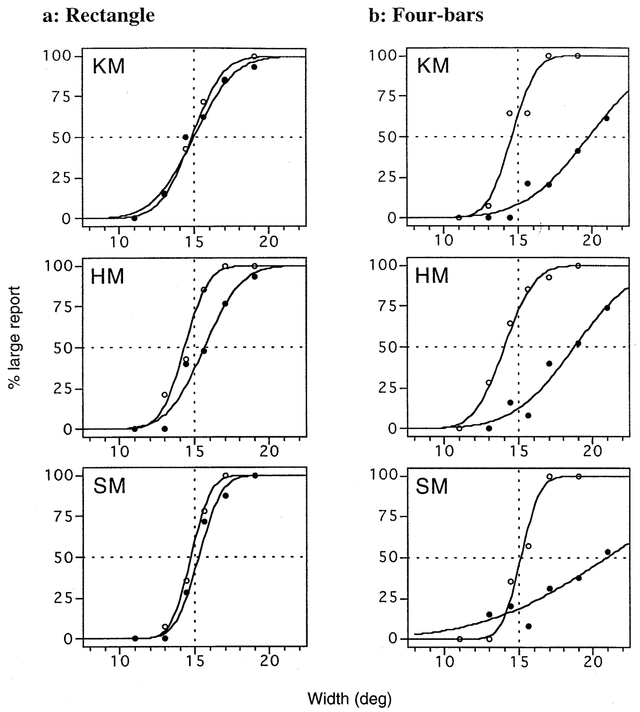

Fig. 4. Percentage of reporting to be larger than the width of the 'large' reference stimulus as a function of the width of the test stimulus; (a) the rectangle condition; (b) the four-bar condition. Solid circles, saccade condition; open circles, fixation condition. The fitting curves were produced by probit analysis (Finney, 1971).

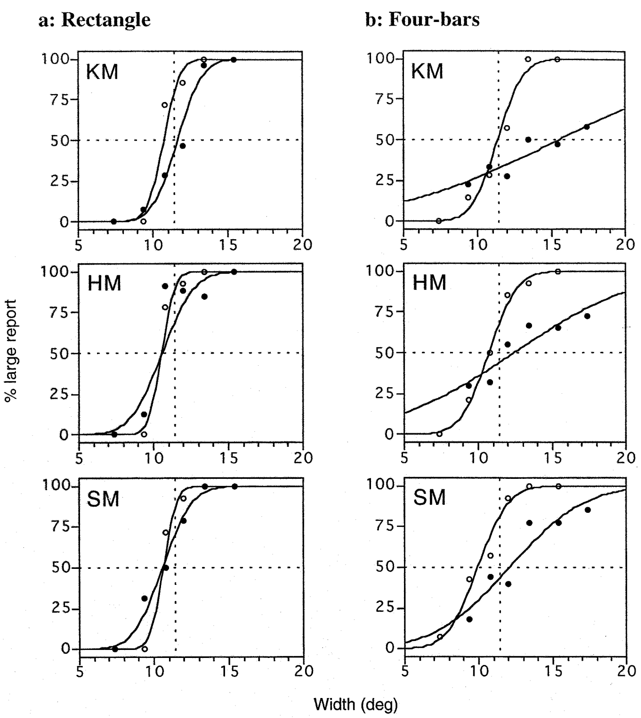

Fig. 5. Percentage of reporting to be larger than the width of the 'small' reference stimulus as a function of the width of the test stimulus; (a) the rectangle condition; (b) the four-bar condition. The way of viewing this figure is the same as in Fig. 4.

4.4. Results and discussion

Figs. 4 and 5 show the percentage of large responses as a function of width for the large and small references, respectively. The solid and open symbols represent the saccade and fixation conditions, respectively. Lines illustrate fitting curves calculated by probit analysis (Finney, 1971).

Fig. 4a and b show the results of the rectangle and four-bar conditions for the large reference. For subjects KM and SM, psychometric functions of the saccade condition in Fig. 4a tended to be consistent with those of the fixation condition, although the curves of the saccade condition tended to shift slightly to the right relative to those of the fixation condition. For subject HM, the psychometric function of the saccade condition in Fig. 4a tended to have more bias toward reporting 'small' responses of test stimuli in comparison with that of the fixation condition than the other subjects. However, the psychometric functions for all subjects in Fig. 4b indicated that 'small' responses of test stimuli increased considerably in the saccade condition in comparison with the fixation condition.

Fig. 5a and b show the results of the rectangle and four-bar conditions for the small reference. In Fig. 5a, the psychometric functions in the saccade condition had almost the same configuration as those in the fixation condition. In Fig. 5b, however, the psychometric functions in the saccade condition had a shallower slope than those in the fixation condition. That is, in the case of the small reference as well as the large reference, the 'small' response of test stimuli increased in the saccade condition as compared with the fixation condition. These results indicate that subjects could correctly judge the width of the rectangle test stimuli presented just before saccades as well as during fixation, and that the apparent width of the rectangle test stimuli differs from that of the four-bar test stimuli in the case of the saccade condition.

Fig. 6 demonstrates the amount of compression in the saccade/four-bars (gray bars), saccade/rectangle (slash bars), fixation/four-bars (dots bars), and fixation/rectangle (open bars) conditions for the large and small references. The amount of compression was defined as shift in point of subjective equality (PSE) from the width of reference. The difference in the width between the PSE and the reference in each condition for the large and small references was statistically analyzed for each subject (t-test).

For the results of the large and small references in subject KM, there were significant differences between the PSE and the width of reference in the saccade/four-bars condition ($P < 0.05$), but no significant differences between them were found in the saccade/rectangle, fixation/four-bar, and fixation/rectangle conditions.

For the results of the large reference in subjects HM and SM, there was a significant difference between the PSE and the width of reference in the saccade/four-bars condition ($P<0.05$). No significant differences were found in the other three conditions. For those of the small reference in subjects HM and SM, however, no significant difference was seen in the saccade/four-bar condition. Conversely, significant differences were seen in three conditions except the saccade/four-bar condition ($P<0.05$). For the small reference, this demonstrates that subjects HM and SM have a bias toward expansion of the width in the saccade/rectangle, fixation/four-bars, and fixation/rectangle conditions, resulting in the compression of the width bias in the saccade/four-bars condition.

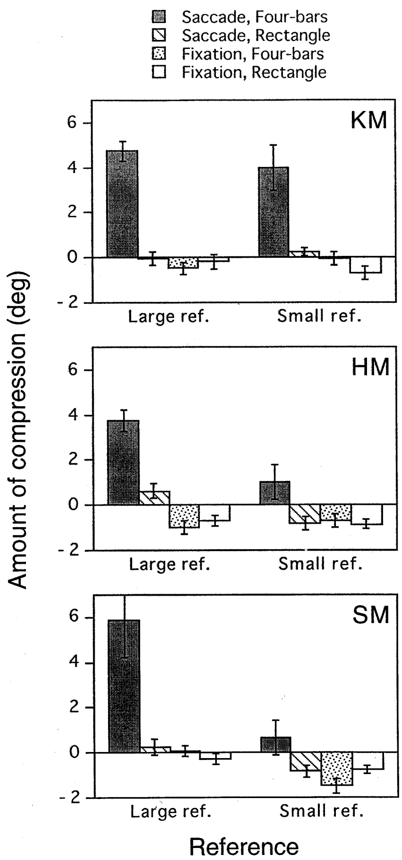

Fig. 6. Amount of compression in the saccade/four bars (gray bars), saccade/rectangle (slash bars), fixation/four bars (dots bars), and fixation/rectangle (open bars) conditions for the large and small references. The amount of compression represents the shift in point of subjective equality from the width of the reference. Representative error bars indicate the S.E. calculated by the probit analysis. The top, middle, and bottom panels represent the results of subjects KM, HM and SM, respectively.

5. Experiment 3: Localization of a flashed bar during saccades

Experiment 3 was conducted to estimate the width change of the rectangle predicted by presaccadic compression of position. Subjects localized the apparent position of a flashed bar presented at the left and right edges of the large and small rectangles used in experiment 2 during saccades.

5.1. Stimuli

A flashed bar (10.0 deg in height and 1.4 deg in width, 15 cd/m^2) was presented for 15.0 ms at the left and right edges of the large and small rectangles used in experiment 2. The positions of the flashed bars were '2.5 and 17.5 deg from the display center' and '4.3 and 15.7 deg from the display center', which corresponded to the left and right edges of the 'large' and 'small' rectangles, respectively. The position of the flashed bar was varied randomly from trial to trial. The ruler, the background on the screen, and the fixation and saccade cues were identical to those in experiments 1 and 2.

5.2. Procedure

The sequence of visual stimuli was identical to that in experiment 1 except for the presentation of multiple-bars. After a randomly selected delay from the saccade onset time (-100 to $+100$ ms), one bar was presented for 15.0 ms at one of four positions (2.5, 4.3, 15.7, and 17.5 deg from the display center). After the saccade, the subject localized the apparent position of the flashed bar by pointing a mouse cursor at that position. Each subject performed eight sessions; a session consisted of 52 trials.

In fixation trials, the sequence of visual stimuli was the same as that described above. The subject was instructed to keep fixating at -10 deg from the display center. Each subject performed five sessions.

5.3. Subjects

Two subjects one male and one female (KM, 29 years old and SM, 29 years old) participated in experiment 3. They had participated in experiment 2.

5.4. Results and discussion

Fig. 7a and b show the apparent position of a flashed bar as a function of time from saccade onset for the large and small rectangle edges, respectively, for subjects KM and SM. The square, diamond, solid triangle, and circle symbols represent the physical positions of the bar flashed at 17.5, 2.5, 15.7, and 4.3 deg, respectively. The solid and open symbols represent the saccade and fixation conditions, respectively.

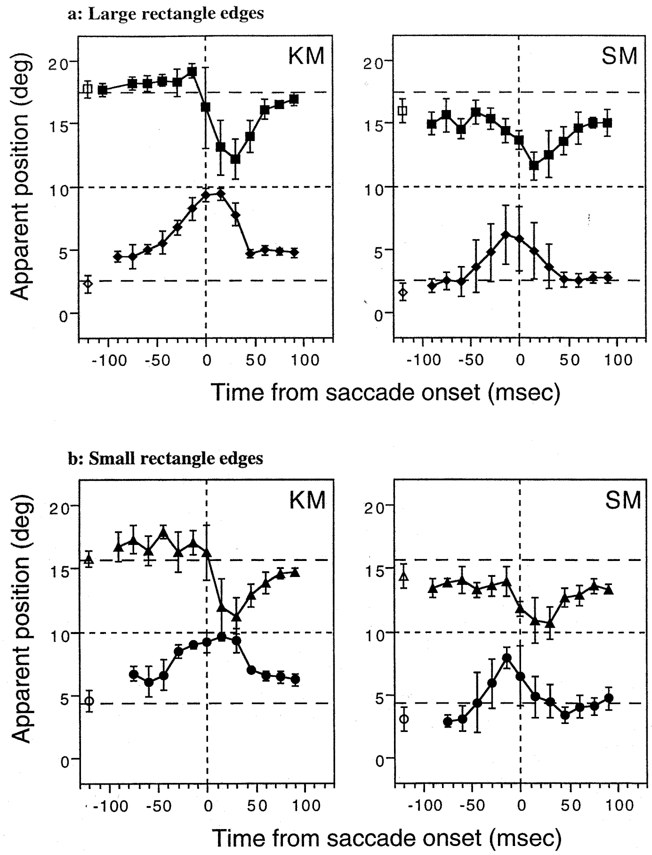

Fig. 7. Apparent position of a flashed bar as a function of time from saccade onset. (a) Large rectangle edges; (b) small rectangle edges. The square, diamond, solid triangle, and circle symbols represent the physical positions of the bars at 17.5 deg, 2.5 deg, 15.7 deg, and 4.3 deg, respectively. The solid and open symbols represent the saccade and fixation conditions, respectively.

For the large and small rectangle edges, the flashed bars presented to the left of the saccade goal were mislocalized in the direction of the saccade, and the flashed bars presented past the saccade goal were mislocalized in the opposite direction of the saccade. The mislocalization reached a maximum within the range of − 50 to 75 ms. Outside this range, the apparent position of the flashed bars was near to the actual position, and this tendency was similar to the results of the fixation condition.

Fig. 8 demonstrates the amount of compression for the long and short distances between the left and right edges in the saccade and fixation conditions. The black bars represent the compression of the positions of the flashed bars. The amount of compression was defined as the position shifts from the actual positions corresponding to the left and right edges of the rectangles. The apparent position of the flashed bar was averaged between − 30 and 0 ms relative to the actual saccade onset. The gray and slash bars represent the compression of the widths of the flashed four-bars and rectangle, respectively, and represent the results of experiment 2.

In Fig. 8a, for subject KM, the amount of the compression of the position of the flashed bar tended to be consistent with that of the width of the four bars for the long and short distances between the edges. For subject SM, the results of the long distance between the edges had the same tendency as subject KM. These results indicate that the presaccadic compression of the width of the four bars is consistent with that of the position of the flashed bar. For those of the short distance between the edges in subject SM, however, the amount of the compression of the width of the four bars was considerably smaller than that of the position of the flashed bar. This result will be discussed in experiment 4. Fig. 8b, however, shows that both the apparent position and the apparent width in all cases remain uncompressed during fixation.

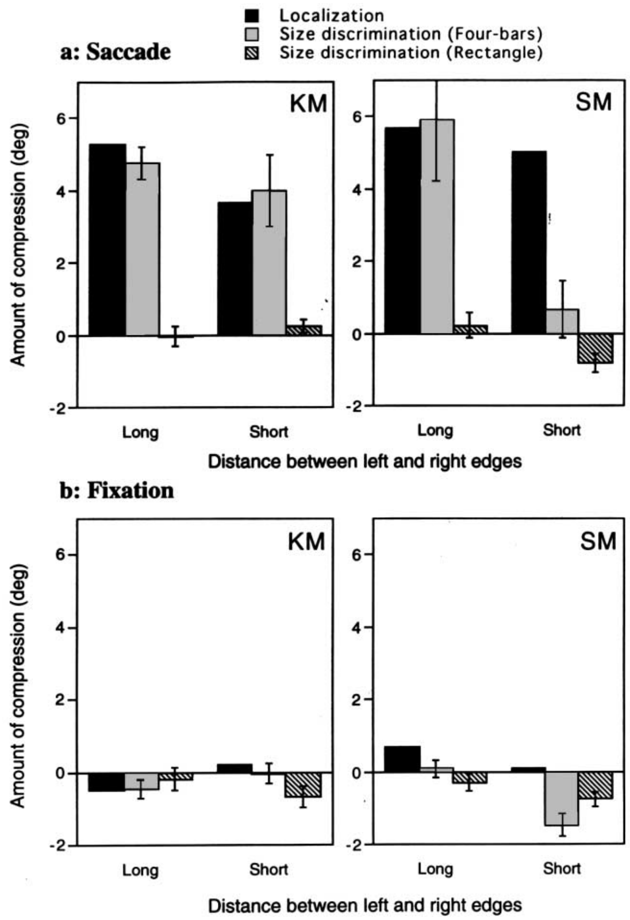

Fig. 8. Amount of compression in the distance between the apparent positions of the flashed bars. (a) Saccade condition; (b) fixation condition. The amount of compression was defined as the position shifts from the actual positions corresponding to the left and right edges of the rectangles. The apparent position of the flashed bar was averaged between − 30 and 0 ms relative to the actual saccade onset. The black bars represent the compression of the positions of the flashed bars. The gray and slash bars represent the compression of the widths of the flashed four-bars and rectangle (the results of experiment 2), respectively.

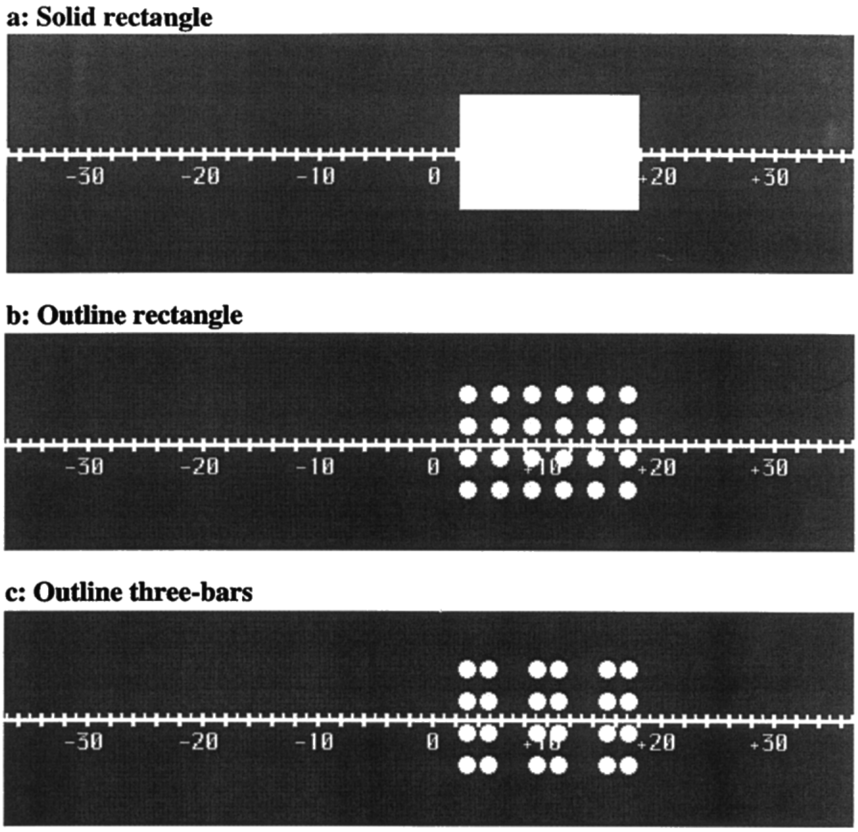

Fig. 9. Visual stimuli used in experiment 4; (a) the solid rectangle; (b) the outline rectangle made of dots; (c) the outline three bars made of dots.

6. Experiment 4: Size discrimination for outline rectangle and three bars made of dots just before saccades

Experiment 2 indicated that the apparent width of the solid rectangle flashed at the saccade goal remained uncompressed just before saccades. If the flashed stimulus is an outline rectangle or outline three bars made of dots, does the compression of the widths of them occur just before saccades? If the position of each dot forming them is attracted to the saccade goal by presaccadic compression of visual space, then both widths of the outline rectangle and the outline three bars should be compressed. However, if the visual system regards the outline rectangle as an object and regards the outline three bars as three objects, then the width of the outline three bars should be compressed, but that of the outline rectangle should be uncompressed. Experiment 4 was designed to measure the apparent width of an outline rectangle made of dots and that of an outline three bars made of dots just before saccades.

6.1. Stimuli

The types of test stimuli are shown in Fig. 9. These stimuli subtended 10.0 deg in height and 15.7 deg in width. In addition, the six types of reference stimuli were used in each case of the flashed stimuli. The reference stimuli were solid rectangles. In the cases of the outline and solid rectangle stimuli, the width of the reference stimulus was selected randomly from '11.3, 13.5, 15.0, 16.4, 18.0, and 20.0 deg'. In the case of the outline three-bar stimulus, the width of the reference stimulus was selected randomly from '9.5, 11.3, 13.5, 15.0, 16.4, and 18.0 deg'. All types of reference stimuli had 10.0 deg in height. The luminances of both test and reference stimuli were 15 cd/m^2. The other stimuli were identical to those used in experiment 2.

6.2. Procedure

The sequence of visual stimuli was identical to that of experiment 2, except for the following: (i) the test stimulus was randomly selected among the outline rectangle, the outline three bars, and the rectangle, (ii) the reference stimulus was randomly selected among the six types of solid rectangles depending on the random selection of the test stimulus, and (iii) the test and reference stimuli were presented for 15.0 ms at the saccade goal. Each subject performed eight sessions; a session consisted of 90 trials. Trials were excluded from the data analysis if the test stimulus was not presented between -30 and 0 ms relative to the actual saccade onset.

6.3. Subjects

One male and two female subjects (KM, 29 years old, SM, 29 years old, and NT, 33 years old) participated in experiment 4. Subject KM had participated in experiments 1, 2, and 3. Subject SM had participated in experiments 2 and 3. Subject NT was naïve in the experiment of saccadic eye movement study.

6.4. Results and discussion

Fig. 10a shows the percentage of large responses as a function of the width of reference stimulus. The open squares, the solid circles, and the open triangles represent the solid rectangle, the outline rectangle, and the outline three bars, respectively. The lines illustrate fitting curves calculated by probit analysis (Finney, 1971).

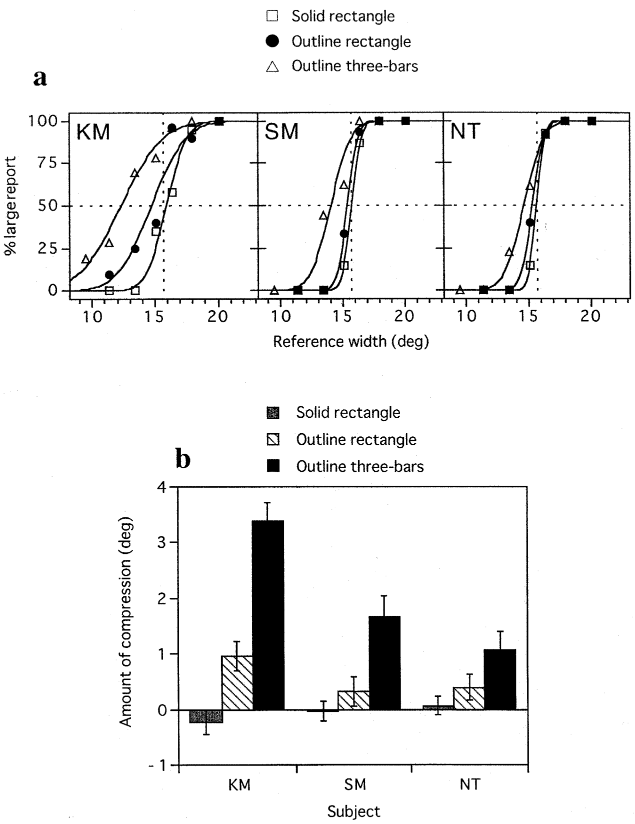

Fig. 10. Apparent widths of the solid rectangle, the outline rectangle, and the outline three-bars stimuli just before saccades. (a) Percentage reporting to be larger than the width of the test stimulus as a function of the width of reference stimulus; the solid rectangle (open squares), the outline rectangle (solid circles), and the outline three-bars (open triangles). Lines illustrate fitting curves calculated by probit analysis (Finney, 1971). (b) Amount of compression; the solid rectangle (gray bars), the outline rectangle (slash bars), and the outline three bars (solid bars). The amount of compression was defined as the shift in PSE from the width of test stimulus. Representative error bars indicate the S.E. calculated by the probit analysis.

Psychometric functions in Fig. 10a indicated that the 'large' responses of the reference stimuli increased in the case of the outline three bars in comparison with the other cases. In the case of the outline rectangle, the 'large' responses of reference stimuli tended to increase slightly as compared with the case of the solid rectangle. All subjects showed these tendencies.

Fig. 10b shows the amount of compression in the cases of the solid rectangle (gray bars), the outline rectangle (slash bars), and the outline three bars (solid bars). The amount of compression was defined as a shift in PSE from the width of the test stimulus. The difference in the width between the PSE and the test stimulus in each case was statistically analyzed for each subject (t-test).

For subject KM, significant differences were seen in the cases of the outline rectangle and the outline three bars ($P < 0.05$). The amount of compression in the case of the outline three-bars was much larger than that in the case of the outline rectangle. No significant difference was found in the case of the solid rectangle. For subjects SM and NT, there was a significant difference in the only case of the outline three bars ($P < 0.05$). However, no significant differences were found in the other cases. That is, these results indicate that the apparent width of the outline three bars is compressed, but that of the outline rectangle tends to be uncompressed. Thus, this suggests that, if a stimulus made of multiple elements is perceived as a single group, the apparent width of the stimulus is uncompressed just before saccades.

For the short distance between the left and right edges of the rectangle in subject SM in experiment 3, the apparent width change of the four-bar stimulus was inconsistent with the width change predicted by presaccadic compression of position (see Fig. 8a). That is, the apparent width of the four-bar stimulus was less compressed, whereas the apparent position of the flashed bar was considerably compressed. This may be explained by considering the results of subject SM in experiment 4. In both cases of the outline rectangle and the outline three bars, the amount of compression for subject SM tended to be smaller than that for subject KM. The difference between subjects SM and KM may be based on a bias of the appearance of the global shape. Subject SM often had the impression that the outline three bars formed one group, not three groups, but subject KM had no such impression. That is, this means that subject SM had the bias to recognize the stimulus made of multiple elements as one group, resulting in less compression of width. Therefore, this suggests that, in the case of the short distance between the edges in experiment 3, subject SM tended to recognize the four-bar stimulus as the outline rectangle. As a result, the apparent width of the four-bar stimulus may be less compressed.

7. General discussion

The present study revealed that presaccadic compression of visual space did not affect the shape of an object at the saccade goal. Experiment 1 showed that the apparent number of multiple bars reduced when they were presented at the saccade goal just before a saccade. This is consistent with the results of Morrone et al. (1997) and Ross et al. (1997). These results suggest that presaccadic compression of visual space occurs at the saccade goal. Experiment 2 showed that the apparent width of the four-bar stimulus presented just before saccades was different from that of the rectangle stimulus presented just before saccades. That is, the apparent width of the four-bar stimulus consisting of separate elements was compressed at the saccade goal just before saccades, but that of the rectangle stimulus consisting of a non-separate and single element was uncompressed at the saccade goal just before saccades. Experiment 3 showed that the presaccadic compression of the apparent width of the four-bar stimulus tended to be consistent with that of the apparent position of the flashed bar. The results of experiment 3 suggest that presaccadic compression of position causes each bar in the four-bar stimulus to be attracted toward the saccade goal, resulting in the width change of the four-bar stimulus. Experiment 4 showed that the apparent width of the outline three-bars was compressed, but that of the outline rectangle was uncompressed. This indicates that, if multiple elements are perceived as a single global shape, the apparent width of the global shape is uncompressed just before saccades. Thus, these results suggest that the perceived shape of not only a solid element but also a group of multiple elements is not distorted during presaccadic compression of visual space.

Why was the perceived shape of the rectangle object uncompressed just before saccades? When the four-bar stimulus was presented at the saccade goal, the visual system could recognize it as four separate objects. Therefore, the perceived location of each object shifted toward the saccade goal just before saccades (Honda, 1993, 1995, 1999; Dassonville et al., 1995; Morrone et al., 1997; Ross et al., 1997; Lappe et al., 2000), resulting in the compression of the distances between bars in the four-bar stimulus. This causes the compression of the apparent width of the four-bar stimulus. In fact, experiment 3 confirmed it. A single element, however, only exists in the rectangle stimulus, although multiple elements are needed for the compression of the apparent width. This explains that the apparent width of the rectangle stimulus is uncompressed just before saccades.

In addition, the results of experiment 4 extend the definition of an object. When the outline rectangle made of dots was presented at the saccade goal, the arrangement of the dots tended to hold together. This indicates that a group of dots is regarded as an object as well as the solid rectangle. However, when the outline three bars were presented at the saccade goal, the arrangement of the dots did not hold together, and the apparent width of the outline three-bars was compressed in the same way as the four-bar stimulus. This indicates that the three groups made of dots are regarded as separate objects and that the location of each group is compressed just before saccades. These findings give a suggestion about what an object is. That is, it is suggested that an object is defined as not only a solid element but also a constellation of multiple elements. This suggestion is consistent with the recent investigation of Blaser, Pylyshyn, and Holcombe (2000). Accordingly, the location of each visual object consisting of multiple elements may be compressed toward the saccade goal in the internal representation of space.

There was a discrepancy between our present findings and part of the findings of Ross et al. (1997). Ross et al. (1997) briefly presented a natural scene around the time of saccade and asked subjects to report how it appeared. They reported that the natural scene appeared compressed when it was presented just before a saccade, and they concluded that presaccadic compression of visual space caused the distortion of the natural scene. However, the natural scene that Ross et al. used includes several object images. For that reason, we speculate that the deformation of object images in the natural scene does not occur, but the apparent location of each object image in the natural scene shifts toward the saccade goal just before saccades, resulting in the impression that the natural scene is deformed.

In addition, our findings seem to be consistent with several studies concerned with the relationship between saccade and visual attention (Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Deubel & Schneider, 1996). Deubel and Schneider (1996), for example, asked subjects to move their eyes toward a specific location and discriminate a feature of a target item. The target item was briefly presented at various locations before the saccade and disappeared before the saccade onset. Finding that the discrimination performance was best at the location of the saccade target, they concluded that visual attention was allocated to the saccade target position. If the shape of the target item presented at the location of the saccade target were compressed just before a saccade, then the discrimination performance would be expected to be worst at its location. However, our findings indicate that the shape of the target item is not compressed at the location of the saccade target during presaccadic compression of visual space. Therefore, presaccadic compression of visual space could not cause the decline of the discrimination performance at the location of the saccade target. This suggests that presaccadic compression of visual space does not prevent the processing of object recognition underlying the attentional mechanism in generating saccadic eye movements.

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