# Salient stimulus attracts focus of peri-saccadic mislocalization

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# Salient stimulus attracts focus of peri-saccadic mislocalization

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ABSTRACT

Visual localization during saccadic eye movements is prone to error. Flashes shortly before and after the onset of saccades are usually perceived to shift towards the saccade target, creating a "compression" pattern. Typically, the saccade landing point coincides with a salient saccade target. We investigated whether the mislocalization focus follows the actual saccade landing point or a salient stimulus. Subjects made saccades to either a target or a memorized location without target. In some conditions, another salient marker was presented between the initial fixation and the saccade landing point. The experiments were conducted on both black and picture backgrounds. The results show that: (a) when a saccade target or a marker (spatially separated from the saccade landing point) was present, the compression pattern of mislocalization was significantly stronger than in conditions without them, for both black and picture background conditions, and (b) the mislocalization focus tended towards the salient stimulus regardless of whether it was the saccade target or the marker. Our results suggest that a salient stimulus presented in the scene may have an attracting effect and therefore contribute to the non-uniformity of saccadic mislocalization of a probing flash.



## 1. Introduction

At times near the onset of saccadic eye movements, our spatial perception can be distorted. While this phenomenon, termed peri-saccadic mislocalization, is not often perceived in daily life, it has been repeatedly shown in controlled laboratory conditions. Specifically, a flashed stimulus presented shortly before or after saccade onset is likely to be mislocalized. The direction and amplitude of mislocalization vary depending on a number of factors, such as the saccade amplitude, the distance between saccade landing point and flash, and the availability of a visual reference (Lappe, Awater, & Krekelberg, 2000). One remaining mystery about this phenomenon is the non-uniformity of the mislocalization. It seems that stimuli flashed at locations between the fixation and the saccade target are perceived to shift in the direction of the saccade, while flashes beyond the saccade target perceptually shift against the direction of saccades, and flashes at the location of the saccade target do not seem to be mislocalized. Thus, the non-uniformity results in a "compression" pattern of mislocalization (Ross, Morrone, & Burr, 1997). Interestingly, such mislocalization non-uniformity is not observed in experiments conducted in complete darkness (Awater & Lappe, 2006; Honda, 1993). Regarding the underlying mechanisms accounting for the compressed mislocalization pattern, it has been proposed that "mislocalization is a consequence of flash retinal signal persistence interacting with an extraretinal signal" (Pola, 2011). Using a saccadic adaptation paradigm, a study by Awater et al. (2005) suggested that the saccadic mislocalization pattern is anchored at the saccade landing point, rather than the saccade target. This interpretation implies that the mislocalization is associated with saccadic eye movement per se, whereas the only role of the saccade target in these experiments is to elicit saccades and is unrelated to the mislocalization effect. However, using the saccadic adaptation paradigm for peri-saccadic mislocalization investigations complicates the interpretation of results, as saccadic adaptation itself may cause perceptual size distortion (Garaas & Pomplun, 2011) and visual localization error (Zimmermann, Burr, & Morrone, 2011).

We speculate that the mislocalization focus being at the saccade landing point as found by many previous studies may be related to the fact that a saccade target is presented there. However, what attribute of the target causes the "compressed" mislocalization pattern? On the one hand, the target acts as a stimulus to elicit saccades towards it, and on the other hand, it is also a primary salient marker on the screen. It has been suggested that compressed mislocalization is associated with visual reference (Lappe,

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Awater, & Krekelberg, 2000). Therefore, it is sensible to assume that the saccade target might actually act as a visual reference and cause the compressed mislocalization. These two roles of the saccade target (visual reference and saccade initiator) were manipulated in this study to investigate the causes for peri-saccadic mislocalization.

## 2. Methods

The design of our experiments was similar to those in previous saccadic mislocalization studies. The basic difference from previous experiments was that we spatially separated the two roles of the saccade target marker as being the saccade landing point and a salient stimulus by asking subjects to saccade to a memorized location while presenting a salient non-saccadic marker a certain distance away from the landing point. Thus, we were able to investigate which role of the conventional saccade target is associated with mislocalization.

### *2.1. Participants*

Two of the authors (GL and TG) and three naive subjects participated in the study. They were all males, normally sighted and had emmetropic vision. The study followed the tenets of the Declaration of Helsinki and was approved by the Institutional Review Boards at the University of Massachusetts Boston and the Schepens Eye Research Institute.

### *2.2. Apparatus*

The experiments were conducted on a 21-in. Dell P1130 CRT monitor with a resolution of 1024 × 768 pixels and a refresh rate of 100 Hz. The monitor spanned 44° × 33° at the observation distance of 36 cm. Eye movements were recorded using an Eye Link II eye-tracker system (SR Research Ltd., Canada), which operates at 500 Hz and has an average accuracy of 0.5°. The position of flashed bars was reported using a standard PC mouse, the cursor of which was only visible during the report phase. All experiments were performed in a normally lit room (688 lux).

### *2.3. Stimuli and procedure*

Two experiments were conducted, with a salient non-saccadic marker being used in Experiment 2 but not in Experiment 1. In Experiment 1, as illustrated in Fig. 1a, subjects made horizontal saccades from a fixation marker (1° crosshair, red) at −10° on a computer screen to a point at + 10°, when the fixation marker disappeared after a random delay (1000–2000 ms), which served as a saccade cue. The saccade goal point was either indicated by a yellow marker (1° round dot, 117 cd/m$^2$) in the control condition of Experiment 1 or memorized by the subjects in the test condition. In the control condition, the yellow dot (saccade target) appeared at the same time as the fixation marker disappeared, and in the test condition the yellow dot was shown before each trial to reinforce the subjects' memory about the location of the saccade goal point. At a randomly chosen time between 100 ms before and 100 ms after the anticipated saccade onset, a vertical white bar (1 × 6°, 120 cd/m$^2$) was flashed for one frame randomly at −9°, 1°, 9°, or 15° relative to the screen center. Using a photocell, we found the actual presentation duration of the bar was approximately 2 ms (measured at 50% brightness points). Subjects reported the perceived location of the flashed bar using a mouse cursor. Saccade latency for each subject was estimated using the same saccade cue before each session. The flash time relative to the actual

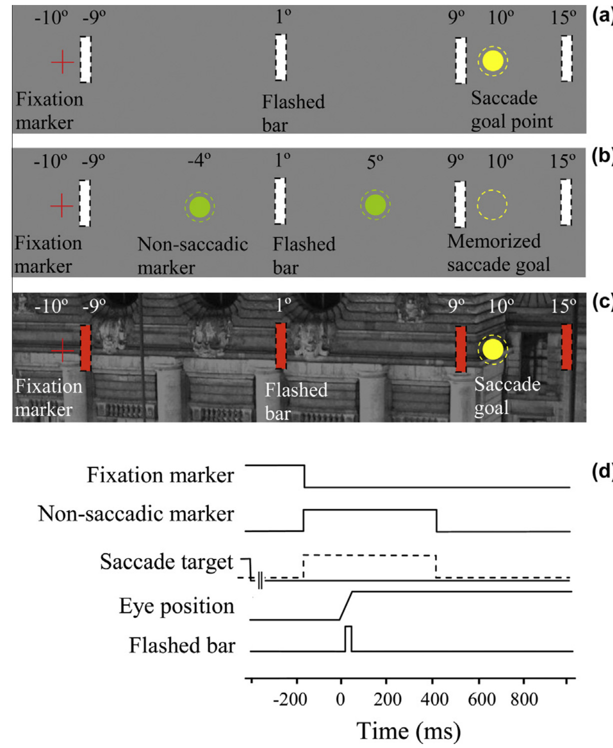


**Fig. 1.** (a) Stimulus presentation in Experiment 1. Visual localization was probed when subjects made saccades from a fixation marker to a saccade goal point. In the control condition, this point was indicated by a saccade target marker, whereas in the test conditions there was no marker but subjects memorized the location instead. (b) Stimulus presentation in Experiment 2. Subjects made saccades to a memorized location, while a salient non-saccadic marker was presented randomly at −4° or +5° at the same time as the saccade cue. (c) Both experiments were repeated with gray scale pictures in the background. To avoid masking of the flashed bar by bright local regions in the pictures, red flash bars were used. (d) Time course of stimulus presentation. When saccades were made to a memorized location, the saccade target disappeared long before (>1000 ms) the eye movement. When saccades were made to the saccade target, it was presented as the fixation marker disappeared and was visible for 600 ms.

saccade onset was precisely determined offline based on the data recorded by the EyeLink system.

In Experiment 2, as illustrated in Fig. 1b, subjects made saccades to the memorized saccade goal point while a salient non-saccadic marker (1° green dot, 88 cd/m$^2$) was presented at the same time as the saccade cue and persisted for 600 ms, appearing randomly at −4° or 5° relative to the screen center. As in Experiment 1, the vertical bar was flashed around the anticipated saccade onset time for one frame randomly at −9°, 1°, 9°, or 15° relative to the screen center. It was not difficult and took typically less than ten practice trials for the subjects to make saccades as instructed to the memorized location despite the presence of the non-saccadic marker.

Experiments 1 and 2 were conducted on a plain black background (6.5 cd/m$^2$), and also repeated with gray-scale pictures in the screen background. Those pictures were randomly selected from 100 real-world scene images, and they were randomly rotated by 0°, 90°, 180°, or 270° to reduce semantic cues. Image pixel values were scaled down not to exceed 128 (half of the full brightness) so that the task-relevant stimuli could stand out while the images were still highly visible. There were many local regions in the pictures that were bright enough to mask the white flashes if they happened to fall on those regions. Therefore, fully saturated red flashed bars (33 cd/m$^2$) were used for the picture background conditions (Fig. 1c).

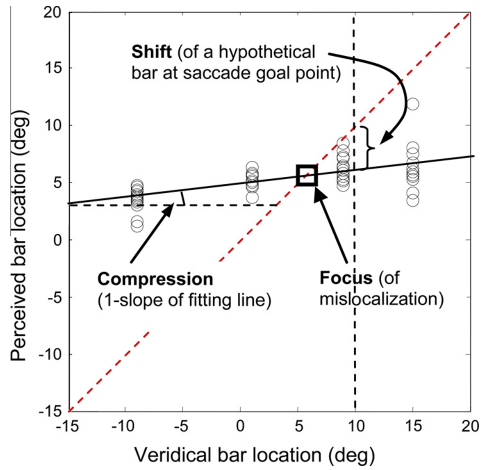


**Fig. 2.** Illustration of calculating compression, shift and focus. A linear regression is performed for trials within a window (10 ms in this paper) of bar onset time (measured relative to saccade onset). The compression ratio is computed as 1 minus the slope of the regression line. The shift is the mislocalization offset of a hypothetical bar flashed at the saccade goal point, estimated based on the regression. Leftwards shift (downwards in this illustration) is negative. Error-free localization is indicated by the red 45° diagonal line. The intersection between the diagonal line and the fitted line is the mislocalization focus. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 2.4. Data processing

Trials that did not meet the eye-movement requirements were excluded from analysis. These requirements were (1) a pre-saccadic fixation on the fixation marker with a deviation smaller than 1° and (2) a saccade landing point closer than 3° to the target location. The actual timing of the flash relative to saccade onset time was determined offline based on the EyeLink recording that included eye movement data and stimulus events.

A method proposed by Maij et al. (2010) was used to quantify the compressed mislocalization by compression ratio and shift. The focus location of the compression pattern is also estimated (see Fig. 2). The compression ratio was calculated as 1 minus the slope of the linear relationship between perceived flash locations ($Y$ axis) and their veridical locations ($X$ axis). The focus location was determined by the intersection of the fitted line and the 45° diagonal line. In other words, the focus was defined as the point where the perceived location would be the same as the veridical location. The shift was defined as the offset of the fit for a hypothetical flash at the required saccade goal point (10° from screen center). The compression ratio for each condition was first calculated using valid trials within a 10-ms-wide moving window, and then the maximum values (i.e., the magnitude) around saccade onset time were used in further statistical analyses. Shift and focus were calculated for the time point of the compression peak.

## 3. Results

Fig. 3 shows typical results obtained from Experiments 1 and 2. Visually, the mislocalization in the test condition (saccades to the memorized location, Fig. 3a) appeared to be substantially smaller than in the control condition (saccades towards the saccade target marker, Fig. 3b). When a salient non-saccadic marker was presented randomly at −4° or +5° and subjects still made saccades to the memorized saccade goal point, the compressed

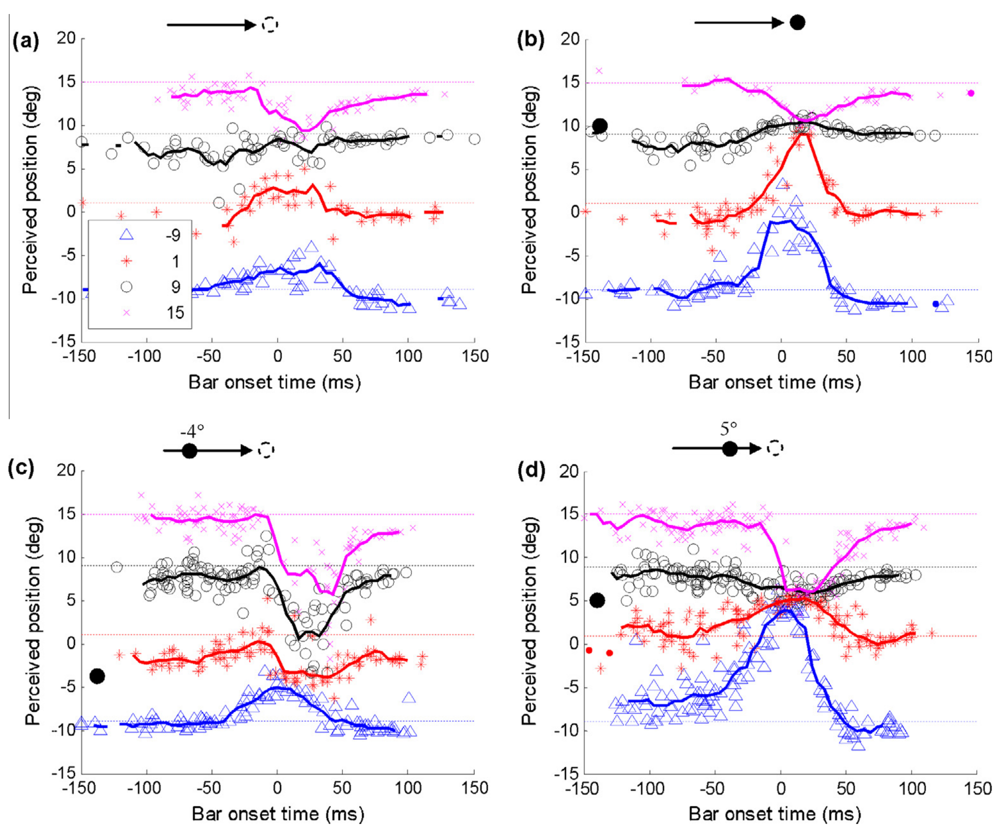


**Fig. 3.** Perceived bar location as a function of its onset time relative to saccade onset. Black solid dots near $Y$-axis indicate the locations of the salient marker. The arrow on top of each figure represents a saccade. These are representative data of subject GL. (a) When there was no saccade target marker and the subject made saccades to a memorized saccade goal point, the mislocalization appeared to be much less pronounced than when a saccade target marker was present. (b) When there was a saccade target marker at the saccade landing point, the flashed bar was perceived to shift towards the target marker, which has typically been shown in many previous studies. (c and d) When the subject made saccades to a memorized location and a salient non-saccadic marker was randomly presented at −4° or 5°, the mislocalization focus shifted towards it.

mislocalization pattern occurred again (see Fig. 3c and d). The compression focus obviously tended to shift towards the non-saccadic marker instead of the saccade landing point. In particular, flashes at 9° (near the saccade landing point), which were barely mislocalized in Experiment 1, shifted towards the non-saccadic marker in Experiment 2 (Fig. 3c).

Fig. 4 shows the peak values of compression ratio, shift, and mislocalization focus for the five subjects for black and picture backgrounds. The Pearson correlation coefficients of linear fitting for compression ratio computation ranged from 0.59 to 0.97 for all conditions of all subjects. Averaged across experimental conditions, the correlation coefficients for the subjects ranged from 0.80 to 0.86.

As Fig. 4 shows, the overall mislocalization patterns seem to be similar for the different backgrounds. Compression was less when there was no salient marker presented, in comparison with conditions with a salient marker presented at either the saccade goal point or another location (Fig. 4a). The shift was smaller when there was no salient marker presented or a salient marker was presented at the saccade goal point (Fig. 4b). However, when a salient non-saccadic marker, also called as distracter here, was presented between the pre-saccadic fixation and the saccade goal point (at −4° or 5°), shift increased negatively, i.e., the hypothetical bar at 10° would be perceived to move away from the saccade goal point and towards the non-saccadic marker. The shift for the far non-saccadic marker at −4° was larger than that for the near distracter at 5°. As Fig. 4c shows, the mislocalization focus results appeared to be consistent with the shift results. When there was no salient

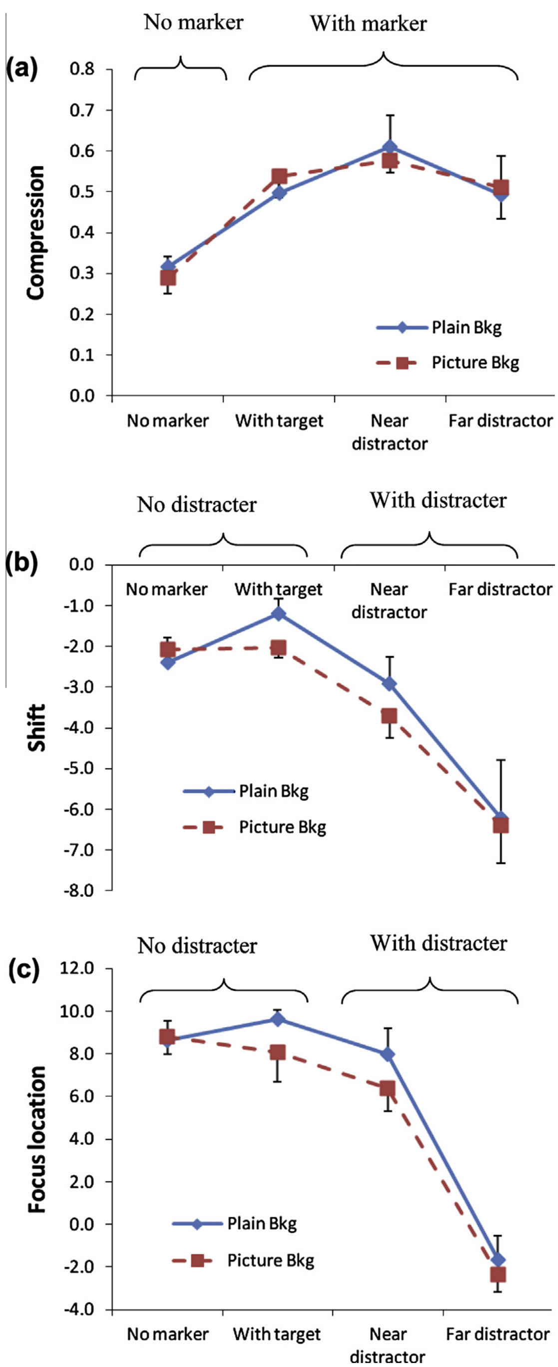


**Fig. 4.** Compression, shift, and focus location results for black and picture backgrounds are very consistent. Error bars indicate standard error of the mean across subjects. (a) Compression in the "memorized goal point" condition with no marker being present anywhere was lower than conditions showing a marker at, near or far from the saccade landing point. (b) When a non-saccadic marker was presented, a flashed bar presented at the goal point would be perceived as shifting towards the non-saccadic marker. This shift increased negatively with the distance between the non-saccadic marker and the saccade goal point. (c) When a non-saccadic marker was presented at −4° or 5°, the mislocalization focus shifted towards it, although the focus was not right on the non-saccadic marker.

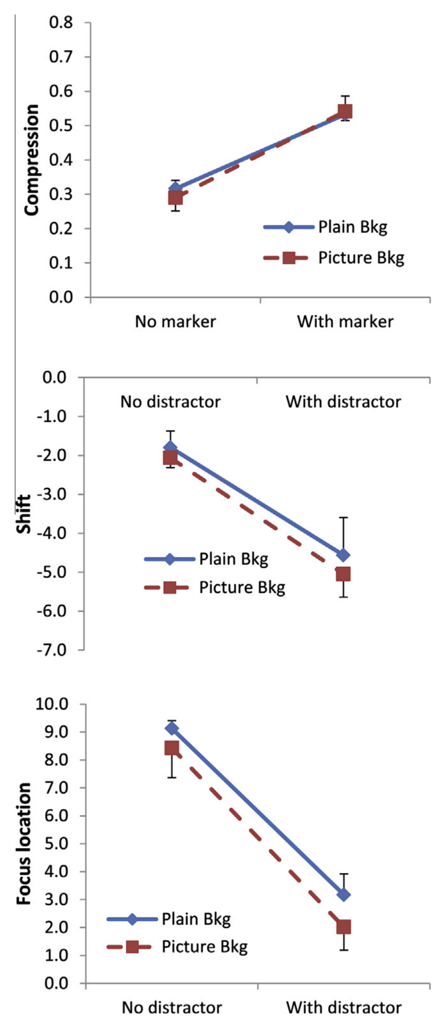


**Fig. 5.** Averaged compression, shift and focus under different experimental conditions. For compression, data with saccade target and near/far distracting markers are combined under the condition "With marker". As can be seen, marker conditions were associated with a higher compression ratio than conditions without saccade target or distracter. For shift and compression focus, data with memorized goal point and with saccade target are combined under the condition "No distracter", and data with near/far distracter are combined under the condition "With distracter". As can be seen, with a distracter presented at +5° or −4°, the compression focus shifted to the left, away from the saccade landing point. Error bars indicate standard error of the mean across subjects.

**Table 1**
Saccade characteristics in different testing conditions. The reported results are averages across background conditions and observers.

| | Saccade latency (ms) | Saccade duration (ms) | Saccade amplitude (deg) | Peak speed (deg/s) |
|---|---|---|---|---|
| Target present | 168.5 | 62.8 | 19.9 | 515.1 |
| No marker | 194.4 | 69.2 | 19.3 | 471.5 |
| Non-saccadic marker | 164.6 | 69.7 | 19.3 | 477.8 |

marker presented or a salient marker was presented at the saccade goal point, the focus location was close to the saccade landing point. However, when a distractor was presented, the focus location moved away from the saccade goal point, especially when the distractor was far away from the saccade landing point. Although the focus was not right on the distracter, the trend of shifting towards distracter is presented.

In order to examine the overall effect of marker or distracter, data under different conditions were combined and tested using repeated measure ANOVA. As shown in Fig. 5a, the compression data for conditions with saccade target and with near and far distracters are grouped, and compared with data for the condition without any marker (saccade to memorized location). Compression with a marker regardless of its location was significantly higher than compression without marker ($p = 0.001$). Background did not have a significant effect ($p = 0.77$). As shown in Fig. 5b and c, shift and focus data for conditions with non-saccadic markers at $-4°$ and $5°$ are grouped, and compared with data for conditions with and without saccade target (i.e. without distracter). In the conventional saccadic mislocalization paradigms where a saccade target is presented at the saccade goal point, as in our with-saccadic-target condition, the mislocalization focus normally lies at the saccade goal point ($10°$ in our case). The non-saccadic marker in our study caused the shift to significantly increase ($p = 0.005$), i.e. shift to the left, and the mislocalization focus to move significantly to the left ($p = 0.001$). Again, background did not have a significant effect on shift ($p = 0.43$) nor focus ($p = 0.24$).

The salient markers used in this study had an effect on saccade characteristics. As shown in Table 1, saccade latency increased by about 17% when the salient marker (saccadic or non-saccadic) was absent. When the salient marker was not at the saccadic landing point, saccade peak speed and saccade amplitude slightly decreased by 8% and 3%, respectively, and saccade duration slightly increased 10%.

It has been shown that peri-saccadic mislocalization may be influenced by changes in saccade peak speed (Ostendorf et al., 2007) and saccade size. However, no correlation between the small changes in saccade characteristics and the dramatic compression pattern change could be observed in our experiments. Specifically, when saccades were made to the memorized location, compression was higher for the non-saccadic marker condition and lower for the no-marker condition (near/far distracter vs. no marker in Fig. 4a), but the peak speed was approximately the same in the two conditions (Table 1).

## 4. Discussion

In this study, we systematically manipulated the two roles of the saccade target - a salient stimulus presented peri-saccadically and the landing point of saccade. It appears that the magnitude as well as the focus of saccadic compression was strongly influenced by the placement of the salient marker, rather than by the saccade landing point. The "attracting" effect of the salient marker on visual localization seems to suggest that it played a role of visual reference. The concept of the visual reference effect on peri-saccadic mislocalization has been discussed and investigated in several previous studies. Honda showed that saccadic mislocalization in a dark room is different from that for an illuminated background in several aspects (Honda, 1993). He postulated that the "visual cue from the visible background" has an effect on peri-saccadic visual localization. Furthermore, by controlling the onset of a ruler on a screen, Lappe's study (conducted in a dark room) showed that the mislocalization can be altered depending on when the ruler is available (Lappe, Awater, & Krekelberg, 2000). He argued that the "visual cue" Honda postulated is actually a post-saccadic visual reference, and this reference generates the compression pattern during a post-saccadic signal retrieval stage (Awater & Lappe, 2006). Using a liquid crystal shutter to control the availability of visual reference, Morrone, Ma-Wyatt, and Ross (2005) argued that the reference does not have to be post-saccadic, in order to induce mislocalization. Whatever the critical timing is, it is clear that visual reference plays a role in peri-saccadic mislocalization. While Lappe and Morrone's studies were conducted in a dark room, our experiments were conducted in a normally lit room (688 lux). Numerous visible objects in the room, such as wall, monitor frame and keyboard, can potentially provide visual references. However, our results show that when no salient marker was presented, the amplitude of mislocalization decreased, even when the screen background was rendered with pictures (Fig. 5a). This suggests that the salient saccade target itself, rather than just anything visible in the scene, is probably the most effective visual reference.

Similar "attracting" effects of a salient marker were also found in two recent studies (Cicchini et al., 2013; Maij et al., 2010). Cicchini et al. (2013) found that a post-saccadic reference near the probing peri-saccadic bar may eliminate compression-like mislocalization, if the reference and the probing bar share the same orientation. Maij et al. (2010) found that when the saccade target is moved during saccades, the perceived location of flashes is affected. In our study, the visual reference role of the saccade target was moved to a location other than the saccade goal point ($5°$ or $14°$ away) and became a salient non-saccadic marker. While the subjects still made saccades to the memorized location, the compression-like mislocalization still occurred (Fig. 3c and d), but the mislocalization focus shifted to the location of the salient non-saccadic marker. The highly visible pictures in the background did not seem to alter the effect of the salient non-saccadic stimulus. Taken together, our results suggest that the compressed mislocalization is largely caused by a salient stimulus, which is not necessarily the saccade target.

Based on data collected in a saccadic adaptation paradigm, Awater and colleagues showed that the mislocalization focus seemed to be at the actual saccade landing point instead of the saccade target in catch trials (equivalent to the non-saccadic marker in our study) (Awater et al., 2005). The finding is inconsistent with ours. We think that this discrepancy is probably due to changes in the spatiotopic visual map associated with saccadic adaptation. It has been recently shown that saccadic adaptation may affect size perception (Garaas & Pomplun, 2011) and visual localization (Zimmermann, Burr, & Morrone, 2011), even during fixations (Zimmermann & Lappe, 2010). It thus appears questionable to use raw data collected with the saccadic adaptation paradigm to prove that the saccade landing point is the mislocalization focus. Interestingly, Awater et al. did find in the same study that if the saccadic adaptation effect was subtracted, the compression focus actually aligned with the saccade target. Thus, their finding would then become consistent with ours.

To our best knowledge, it is unclear what mechanisms can account for the "attracting" effect of the salient stimulus. We think that it might be related to the fact that the flash is very short and occurs around the time of saccades, but the fundamental question is in what way the characteristics of the flash result in mislocalization. We have previously shown that peri-saccadic visual localization is subject to errors in the "where" visual pathway but not in the "what" pathway, by comparing the perceived location and size of a flashed horizontal bar (Luo et al., 2010). Based on this postulated framework, the mechanism is unlikely to originate from the "what" visual pathway. Indeed, the visibility of flashed stimuli ("what" vision) during saccades is not necessarily low. Short flashes are not subject to significant motion smear and are hardly affected by passive saccadic suppression. It has been recently shown that visual contrast sensitivity is largely unaltered during saccades when the passive suppression process (including visual masking and motion smear) is prevented (Garcia-Perez & Peli, 2011). Therefore, the visual perception of flashed objects during saccades should be similar to that during fixations.

The "attracting" effect of the salient stimulus on peri-saccadic mislocalization is probably associated with another aspect of the flash: spatial coding or "where" vision. Unlike object vision coding, spatial coding of flashes during saccades may not be well established or may be disturbed (Krekelberg et al., 2003). The localization of peri-saccadic flashes is therefore subject to uncertainty. If visual reference is somehow used in pinning down the location, as Hamker et al. speculated (Hamker, Zirnsak, & Lappe, 2008), the spatial perception of the flash might be interfered by a salient object with a strong spatial coding signal. However, Hamker, Zirnsak, and Lappe (2008) did not find that cuing flash position, using an always-on anchor to reduce uncertainty about flashes, changed the pattern of mislocalization towards the saccade target. We believe that this result was due to the fact that they used a salient saccade target, while in our Experiment 2 there was no saccade target, and a salient non-saccade marker "attracted" flashes.

Interestingly, as Figs. 3a and 4a show, there was still a small amount of compressed mislocalization focused on the saccade target location, even when no salient stimulus was presented. This is probably because spatial coding of the saccade landing point is needed in saccade planning, and the memorized spot might serve as a visual reference similarly to a real object. When the subjects needed to deploy attention to the memorized spot, that spot might be considered as effectively somewhat salient, since the most important nature of saliency is to attract attention. Of course, the saliency of such featureless spot is constructed by a top-down attention mechanism, unlike the non-saccadic marker, whose saliency is derived through a bottom-up pathway even though the subjects tried to ignore it when making a saccade. It would be interesting to show that both types of saliency have similar effects on peri-saccadic visual localization. A limitation of the present study is that the saliency level of the non-saccadic marker was not thoroughly manipulated and no explicit attention factor was included, while we did use a bright color marker on gray picture and black backgrounds. Further investigation on this topic may contribute to a better understanding of the saliency and attention factors contributing to visual localization.

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