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SPATIAL INDEPENDENCY IN PERCEIVED LENGTHS OF SACCADE-INDUCED IMAGES

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When observers make a saccade across a flickering light dot at the same location, they usually perceive an array of dots (Hershberger, 1987). This phenomenon can be exploited for presenting two-dimensional images using only a single dimensional light source such as a single column of LEDs or laser projectors. In the present study, we investigated whether the perceived length of saccade-induced images is modulated by relative position of the light source and the observer. Participants were presented with a continuous laser-lit dot at several different locations adjacent to a saccade target. On each trial, they were required to make a saccade from a fixation point to the saccade target and then to localize the two endpoints of perceived line induced by the saccade. The results showed that the perceived length of the saccade-induced lines was approximately a half of the distance between the fixation point and the saccade target regardless of the light source location.

Key words: saccade, saccade-based display, phantom line, spatial characteristics

When observers make a horizontal saccade across a flickering or continuously lit dot in a dark room, they perceive an array of dots or a line, respectively (Fig. 1a). The array of dots is referred to as a "phantom array" (Hershberger, 1987; Hershberger, Jordan, & Lucas, 1998) whereas the line is called a "phantom line" (Noritake, Kazai, Terao, & Yagi, in press).

This phenomenon can be used to display two-dimensional images using a single column of light sources such as LEDs or laser projections. When each light source in the column is turned on and off during a saccade, an observer perceives a two-dimensional image (Fig. 1b). We will refer to such a display as a saccade-based display. The saccade-

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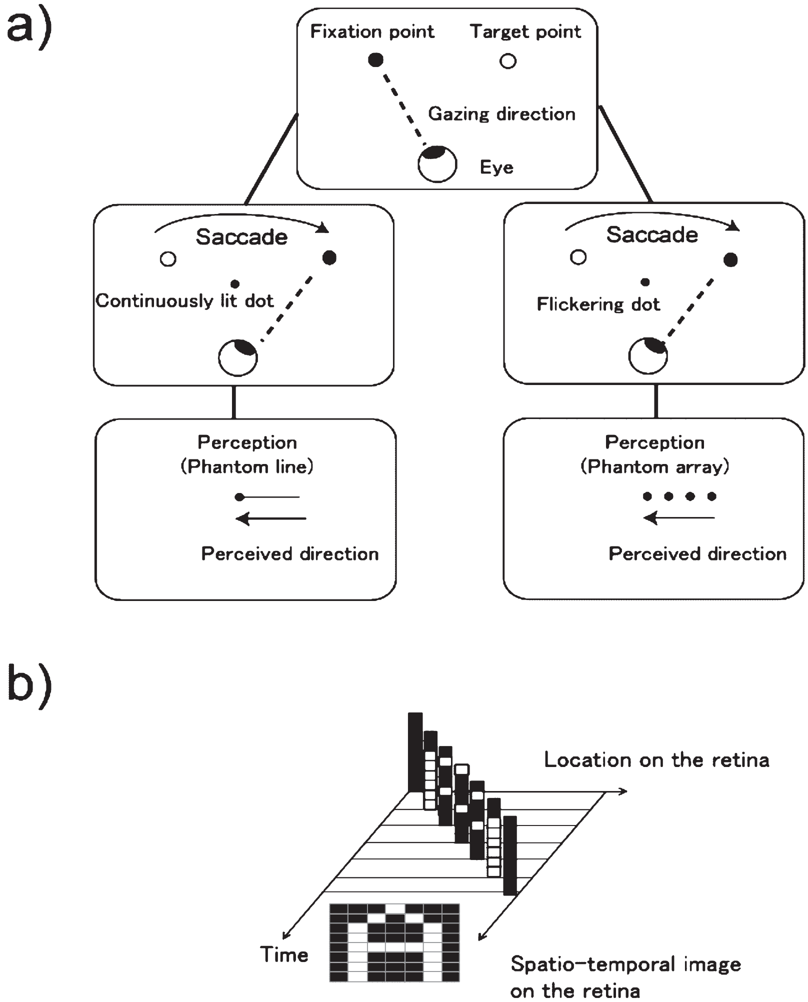

Fig. 1. a) Perception of the phantom array or the phantom line. When observers make a horizontally rightward saccade across a flickering dot or a continuously lit dot, they perceive a phantom array or a phantom line, respectively. The filled or open circle indicates that the light is turned on or off, respectively. The dashed line from the eye indicates the direction of the gaze. b) Schema of the perceived images by a saccade-based display. The lights are turned on and off during a saccade, and the images are induced by an observer's saccade.

based display can be employed in advertising because the presentation of the two-dimensional images using this method is likely to attract attention of a casual observer. In addition, the saccade-based displays tend to be cheaper, require less energy, and occupy less space than full two-dimensional displays such as CRT. This type of display can also be used as a communication tool in the fields of art and entertainment industry.

To fully exploit possible applications of the saccade-based displays, it is necessary to understand basic characteristics of such displays, for example, whether the perceived size of saccade-based images depends on the location of the display relative to the trajectory of the saccade. The previous research has already revealed some of the basic characteristics of such displays. Hershberger and his colleagues (Hershberger, 1987; Hershberger, et al., 1998; Jordan & Hershberger, 1994) presented a flickering light located between a fixation point and a saccade target and found that the length of the phantom array was approximately half as long as the actual saccade amplitude (Fig. 1a). Watanabe, Maeda, and Tachi (in press) showed that when observers made horizontal saccades with different amplitudes across a flickering light presented at similar position to the study in Jordan and Hershberger (1994), the perceived lengths of the phantom line highly correlated with the saccade amplitude and the ratios of perceived lengths to saccade amplitudes were about 0.5 regardless of the saccade amplitudes.

Moreover, the recent research has revealed that the phantom array or line is perceived only when the duration of a flickering dot overlapped the execution of a saccade (Noritake et al., in press; Sogo & Osaka, 2001) and is not influenced by flashes of light presented before or after a saccade (Watanabe, Noritake, Maeda, Tachi, & Nishida, 2005). Noritake et al. (in press) showed that the perceived lengths of the phantom array (FLICKER condition) were longer than those of the phantom line (CONTINUOUS condition) even though the saccade amplitudes in the FLICKER and CONTINUOUS conditions were similar. This result parallels the findings obtained with the real arrays of lights or lines; the observers of real arrays or lines also report that the length of arrays vs. lines is longer even though their eyes remain stationary.

Although the previous studies have examined the relationship between the perceived length of phantom arrays or lines and the amplitude of the saccades, the location of the light source was always fixed between the fixation point and the saccade target. The main objective of the present study is to investigate whether the length of phantom line depends on the spatial position of the light source when the light source is located both within and beyond the saccade's intended trajectory, that is, when the light source is located between the fixation point and the saccade intended target location and when it is located beyond the saccade intended target location. Participants were presented with a continuous laser-lit dot at several different locations adjacent to the saccade target. Two of the locations were between the fixation point and the saccade target and two were beyond the saccade target. On each trial, participants were required to make a saccade from the fixation point to the saccade target and then to localize the two endpoints of perceived line induced by the saccade. Based on Watanabe, Maeda, and Tachi (in press) results, we expected that the perceived line length would be correlated with the saccade amplitude and the ratio between the two would be approximately 0.5 at least when the light source are located between the fixation point and the saccade. However, another possibility is that the perceived line length and the ratio between the perceived line length and the saccade amplitude may vary as a function of the saccade amplitude especially when the light source is located beyond the saccade target.

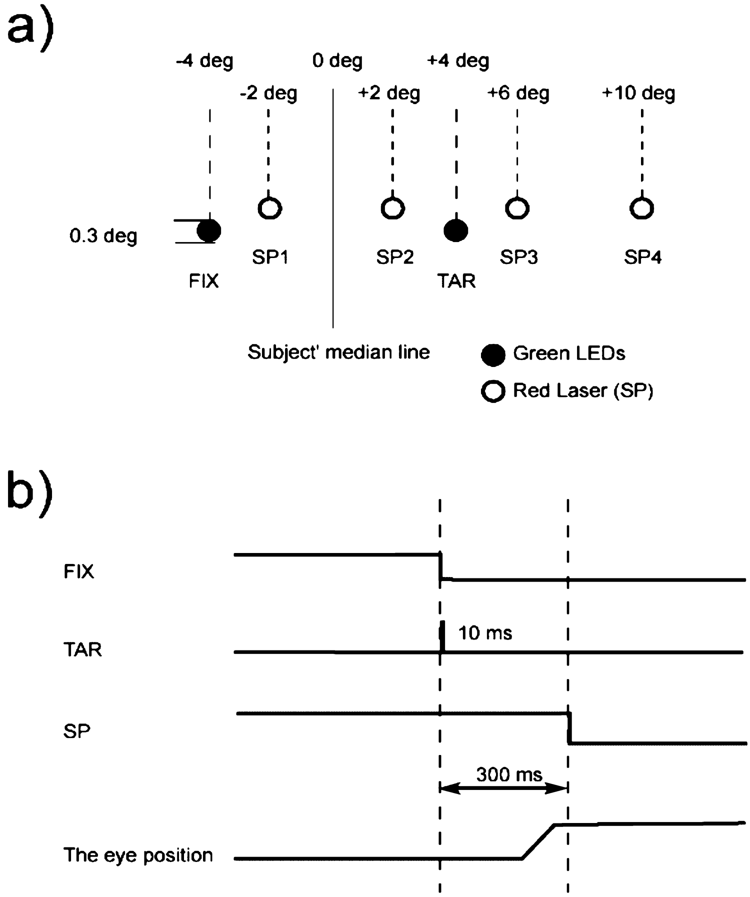

Fig. 2. a) Spatial alignment of the FIX, TAR, and SPs, b) Time chart of the FIX, TAR, SPs, and eye positions.

METHOD

Participants:

Three males (A.N., J.W., and H.A.) and one female (K.Y.) participated in the experiment. They had normal or corrected-to-normal visual acuity with binocular vision. Two of the participants are authors of this study and the others were naïve to the objectives of the experiment.

Apparatus:

The experiment was performed in a dim room with ambient lighting. The participants were seated with their heads stabilized on a chin rest. Fig. 2a contains a schematic representation of the spatial assignment for the fixation point (FIX), the saccade target (TAR), and the possible stimulus locations (SPs). Two green LEDs (0.5 degrees in diameter, 8.3 cd/m^2) placed at eye level were positioned at 4 degrees to the left and to the right of the participants' median lines for the FIX (–4 degrees) and for the TAR (+4 degrees), respectively. A red laser pointer (diameter: 0.5 degrees, 2.2 cd/m^2, laser: class II) was projected at one of four possible visual-stimulus locations (SPs), –2 degrees (SP1), +2 degrees (SP2), +6 degrees (SP3), and +10 degrees (SP4) along the horizontal axis. A micro IC (PIC16F877 Microchip Inc.) controlled the presentation time of the FIX, the TAR LEDs, and the locations of the laser projections.

A screen of the FIX, TAR, and SPs was 113 cm far from the participant's eyes. The participants held two red laser pointers (diameter: 0.1 deg, laser: class II) in each hand for the localization of the perceived points. Since no limitations on motion were established, the participants could freely handle the laser pointers. A digital camera placed under the chinrest was used to obtain images showing the locations at which the participants pointed to both endpoints of the perceived images using the laser pointers.

A computer recorded the presentation time of the FIX, TAR, and SPs with a digital I/O board equipped with an accuracy of 1 microsecond. The eye movements of each participant's left eye were recorded by a VideoEyeTrackerToolbox (Cambridge Research System) with a resolution of 0.5–0.25 degrees. The data were sampled at a rate of 50 Hz. These eye-position data were used to calculate the time of the SPs offset from the saccade offset and check drifts before and after saccades.

Procedure:

Each block of the experiment began with a calibration procedure in which the participants sequentially fixated upon one of three locations: –6, 0, and +6 degrees. We calculated the eye positions in degrees based on the calibration data. The time charts of the experiment are shown in Fig. 2b. At the beginning of each trial, one SP and the FIX were simultaneously turned on. The participants were asked to fixate on the FIX. After a random duration (0.5 to 1 s), the FIX was turned off and the TAR (saccade target) was turned on for 10 ms immediately after the disappearance of the FIX. The participants made a horizontal 8-degree saccade to the TAR. The presented SP disappeared 300 ms after the TAR offset. When the participants perceived the phantom line, they were asked to simultaneously localize both perceived endpoints of the phantom line using the hand-held laser pointers. When they perceived a single dot instead of the phantom line, they were asked to localize it by using one of the laser pointers. The participants were also asked to localize points as soon as possible to avoid potential memory distortion of the perceived location (Sheth & Shimojo, 2001). Immediately after the localized points became stable, photographs were taken to obtain images of the localized points. The inter-trial interval (ITI) was at least more than 1 s. In the experiment, each block consisted of 20 trials, and each participant ran at least 12 blocks.

We excluded trials in which the participants did not make normal saccades based on the following criteria: 1) when the saccade amplitudes were less than 5.0 degrees; 2) when the saccade latencies were less than 120 ms; 3) when there were some eye movements, including corrective saccades or blinks; and 4) when the saccade latencies were more than 260 ms. The reason for the last criterion was to exclude trials in which the presentation of the stimulus finished before the saccade terminated. The ratios of trials in which participants did not perceive the phantom line to those in which they perceived it in normal saccades trials were calculated. The mean values across participants in perceived lengths, saccade amplitudes, and ratios of perceived lengths to saccade amplitudes.

RESULTS AND DISCUSSION

Table 1 shows proportion of trials for which the participants perceived the phantom line out of all trials with normal saccades for each stimulus location and for each participant. On average, the participants perceived the phantom line on 90.9 % of all trials with normal saccades and there were no significant differences between the proportions across the stimuli positions (ANOVA, $F(3, 9)=2.86, p=.097$).

Fig. 3a shows the perceived lengths of the phantom lines for each stimulus location averaged across all participants as well as for each participant. The perceived lengths of the phantom line were similar across all stimulus locations (ANOVA, $F(3, 9)=.83, p=.51$). In contrast, Fig. 3b shows that the saccade amplitudes were similar for SP1 and SP2 locations but were larger for SP3 and especially for SP4 location ($F(3, 9)=11.44, p<.01$). Follow-up, multiple comparison LSD tests revealed that the saccade amplitudes at SP3

Table 1. Proportions of Trials Reported as the Phantom Line to Those With Normal Saccades

SUBJECT	STIMULUS POSITION			
	SP1	SP2	SP3	SP4
A.N.	1.00 (26)	1.00 (36)	0.95 (44)	0.87 (45)
J.W.	0.86 (7)	0.75 (32)	0.70 (46)	0.72 (46)
H.A.	1.00 (30)	0.96 (45)	0.97 (40)	0.86 (35)
K.Y.	0.94 (33)	1.00 (24)	1.00 (31)	0.97 (34)

Note: The value in the bracket indicate the numbers of all normal saccade trials at each stimulus position.

and SP4 were significantly larger than those at SP1 and SP2 ($p<.05$). These latter results are consistent with the prior research findings showing that the saccades tend to end at the geometrically averaged location of the two competing simultaneously presented targets (e.g., He & Kowler, 1989).

In combination, the above results indicate that the perceived length of the phantom line was independent of the saccade amplitudes. Consequently, the ratios of perceived lengths to saccade amplitudes, shown in Fig. 3c, were similar for SP1 and SP2 locations (0.47 and 0.48) but much smaller for SP3 (0.37) and SP4 (0.33) locations. An ANOVA revealed significant differences in stimulus locations ($F(3, 9)=9.88$, $p<.01$), and follow-up multiple comparisons LSD tests revealed a significant difference between SP1 and SP2 vs. SP3 and SP4 ($p<.05$). Our results are consistent with Hershberger (1987) finding that the ratio of the perceived length and saccade amplitude is approximately 0.5 when stimuli are presented between the fixation point and the saccades' intended end. However, our results for SP3 and SP4 locations suggest that the ratio of the perceived length and the saccade amplitude is not fixed but varies depending on particular conditions. Specifically, as shown by our data, the ratio decreased substantially for SP3 and SP4 locations, that is, when the stimuli were located beyond the saccades' intended end.

Fig. 4 shows mean locations of the phantom-line endpoints (black lines), mean locations of the saccades' onsets (open right-pointing triangles) and offsets (open left-pointing triangles), and locations of the four stimuli (filled circles) for each of the four stimuli conditions. The data in Fig. 4 show that the phantom lines were perceived even when the stimuli were located beyond the saccades' offsets and that the length of the phantom lines did not decrease even under these conditions.

CONCLUSION

Our results indicate that the perceived length of the phantom lines was similar and independent of the saccades' amplitudes. Moreover, our results show that the phantom lines are perceived even when the stimuli are located beyond the saccades' offsets and that the perceived length is not decreased even under these conditions. We are presently

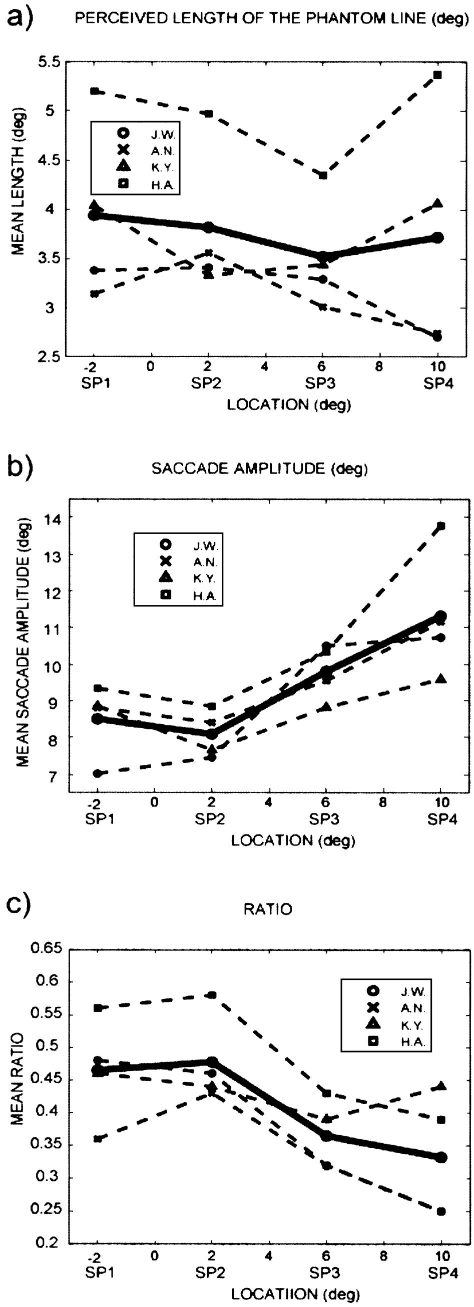

Fig. 3. Each point indicates a) the perceived length, b) the saccade amplitudes, c) the ratio of perceived length to saccade amplitude in each stimulus position for each participant (dashed line). The thick solid line indicates the grand mean values across four participants.

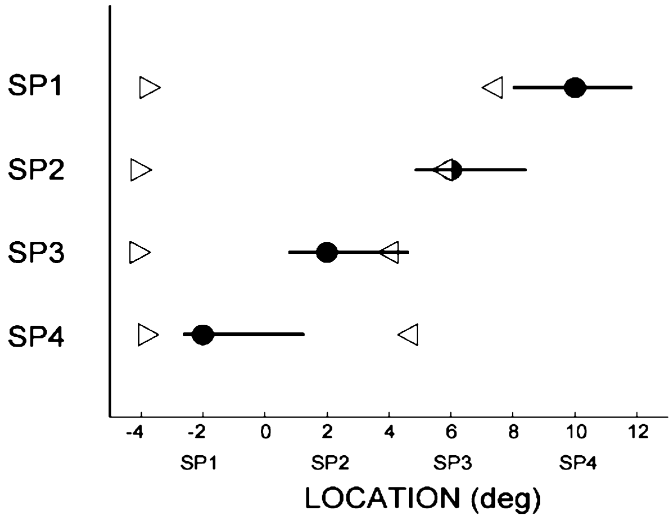

Fig. 4. Schematic illustration showing mean locations of the phantom-line endpoints (black lines), mean locations of the saccades' onsets (open right-pointing triangles) and offsets (open left-pointing triangles), and locations of the four stimuli (filled circles) for each of the four stimuli conditions (SP1–4).

investigating whether the perceived length of the phantom lines depends on the eccentricity and distance of the stimulus from the saccades' trajectory.

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