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The attenuation of perceived image smear during saccades

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Abstract

The perception of image smear for a target flashed during a saccade is attenuated if the target remains visible after the eye movement ends, a result that has been attributed to backward masking. In this experiment, normal observers matched the length of perceived smear in two conditions that were designed to produce comparable retinal stimulation and, therefore, similar amounts of masking. In the *saccade* condition, a small stationary bright dot was illuminated for 5–640 ms, starting near the onset of a horizontal saccade. In the *fixation* condition, the bright dot moved right or left at 50, 100, or 200° s^{-1} while the observer viewed a stationary target and, thereafter, remained stationary. As expected, in the saccade condition perceived smear first increased and then decreased as the duration of the flashed dot extended beyond the duration of the eye movement. However, perceived smear was substantially greater in the fixation condition for stimulus durations that were longer than the period of dot motion. Under the conditions of our experiment, the attenuation of perceived image smear during saccades is attributable primarily to the operation of an extraretinal eye movement signal, rather than to backward masking.

Keywords: Saccade; Motion smear; Masking; Extraretinal signal

1. Introduction

Normally, we remain unaware of the retinal image smear produced by stationary targets during saccadic eye movements. Matin, Clymer, and Matin (1972) showed that smear is perceived for a target flashed in darkness during a saccade, but the extent of perceived smear decreases if the target remains visible after the saccade is completed (see also Kennard, Hartmann, Kraft, & Glaser, 1971; Mateeff, 1978). Matin et al. attributed this reduction in perceived smear to metacontrast masking of the smeared image by the post-saccadic stationary image of the target.

Metacontrast masking has been offered also as an explanation for the relatively small extent of perceived smear that is produced by motion of a target's image across the retina, when the eye is stationary (e.g. Di Lollo & Hogben, 1985; Castet, 1994; Purushothamen, Ögmen, Chen, & Bedell, 1998). The perception of extensive smear would be expected on the basis on the relatively long duration within which the human visual system can integrate information (e.g. Roufs, 1972; Burr, 1981). Indeed, considerable smear is typically perceived for an isolated target that moves against a dark (Bidwell, 1899; McDougall, 1904) or homogeneously illuminated background field (Lubimov & Logvinenko, 1993; Chen, Bedell, & Ögmen, 1995 however, also see Burr). On the other hand, the extent of perceived motion smear for an array of bright random dots increases with the duration of image motion only up to approximately 50 ms, and may decrease for longer presentation durations (Burr, 1980; Hogben & Di Lollo, 1985; Chen et al.). This substantial difference in the extent of perceived smear for an isolated moving spot or line versus multiple moving targets is consistent with a role for metacontrast masking in the attenuation of perceived motion smear (Di Lollo & Hogben; Chen et al.; Purushothamen et al.).

Bedell and Lott (1996) found that perceived image smear for a physically stationary target during smooth

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pursuit is less than the smear perceived during comparable motion of the retinal image when the eye remains stationary. In both conditions of this experiment, an isolated bright dot was presented against a homogeneously illuminated, photopic background field. Because the retinal image events were similar during the pursuit and fixation conditions in this study, the reduction in perceived image smear during pursuit could not be attributed to masking. Rather, Bedell and Lott concluded that an extraretinal eye movement signal contributed to the attenuation of perceived image smear during pursuit.

The purpose of this study was to compare the perception of smear that results when a target is flashed during a saccadic eye movement to the smear perceived during comparable retinal stimulation when the eye remains still.

2. Methods

The length of perceived image smear was determined for an 1-pixel bright dot (4.2 s arc, nominally), presented on a Hewlett Packard 1311B oscilloscope at a distance of 2 m. A $9 \times 10°$ homogeneously illuminated background field of 2.1 cd m^{-2}, reflected from a plate beam splitter, masked visible phosphor persistence of the dot stimulus. This was verified by determining that the dot could not be detected against the background field if an electronic shutter opened simultaneously with stimulus offset (Sun & Irwin, 1987; Groner, Groner, Müller, Bischof, & Di Lollo, 1993). Both the oscilloscope and background field were viewed monocularly.

In the saccade condition, horizontal eye position was sampled at 1 ms intervals using an Applied Science Laboratories (Waltham, MA) model 210 Eye Trac, which compares diffusely reflected infrared light from the nasal and temporal limbi. This instrument provides a linear signal of horizontal eye position over a substantially greater range of eye positions than measured here, with a temporal frequency response that falls by 3 dB at 100 Hz. Nominal sensitivity is 15 min arc or better in the absence of rigid head restraint, as in the experiments reported here. At the beginning of each session, the observer was instructed to follow a fixation cross that jumped between three pre-set locations, separated horizontally by 69 min arc. The target remained at each location for 2 s, and the averaged eye position from 0.75 to 1.75 s after each target jump was used for calibration. Eye position signals were read into a PC computer using a 12-bit A/D converter (Scientific Solutions, Solon, OH) and the eyetracker gain was set to approximately 100 digital units per degree.

Each saccade trial began when a fixation cross appeared randomly 2.3° left or right from the center of the screen. The observer fixated on the cross and signaled the computer that he or she was ready by pressing a button. After a delay of 200 ms, the fixation cross was displaced instantaneously to a new location, 4.6° away on the opposite side of the monitor, where it remained visible for 1.2 s. The computer detected the onset of the observer's saccade using a velocity criterion, which varied across sessions from 11 to 40° s^{-1}, depending upon the position of the infrared sensors and the gain settings of the eyetracker. As soon as the onset of the saccade was detected, the 1-pixel bright dot was displayed at the middle of the oscilloscope screen, 2° below the observer's line of sight. Dot duration varied randomly between 5 and 640 ms from trial-to-trial. Trials were discarded automatically if the saccade was detected less than 20 ms following the displacement of the fixation cross. Trials on which triggering did not coincide with the onset of the saccade were also rejected.

In the fixation condition, the observer viewed a fixation cross at the center of the oscilloscope screen and signaled with a button press when he or she was ready. After a 200-ms delay, a 1-pixel bright dot moved randomly leftward or rightward along a horizontal path, 2° below the stationary fixation cross. The velocity of dot motion was chosen to approximate the peak saccadic velocity of our observers and was either 200, 100, or 50° s^{-1} in different sets of trials. The endpoint of the dot's motion was 2.3° left or right of the display center, with a maximum path length of 4.6°. The dot's duration varied randomly from 5 to 640 ms from trial-to-trial; when this duration was longer than needed to travel 4.6°, the dot remained stationary at its terminal position for the remaining time.

After each saccade or fixation trial, the observer's task was to match the complete extent of perceived smear produced by the bright dot. Matches were obtained by adjusting the length of a bright horizontal line, presented 2° below a stationary fixation cross. The sequence of events for both saccade and fixation trials is depicted in Fig. 1.

In both the saccade and fixation conditions, the contrast of the target dot was set to specific multiples of its detection threshold, as determined at the beginning of each experimental session (see Table 1). For the saccade condition, a 10-ms presentation of the stationary dot was triggered when the observer made a horizontal saccade. As described above, the saccadic target was 4.6° left or right of fixation and the dot was presented randomly 2° above or below the observer's line of sight. In the fixation condition, a moving dot was presented for 10 ms 2° above or below the cross used to constrain the observer's fixation. After each presentation, the observer pressed one of two buttons to signal whether the target was above or below the fixation or saccadic target. Thresholds were determined using an adaptive staircase procedure (Watson & Pelli,

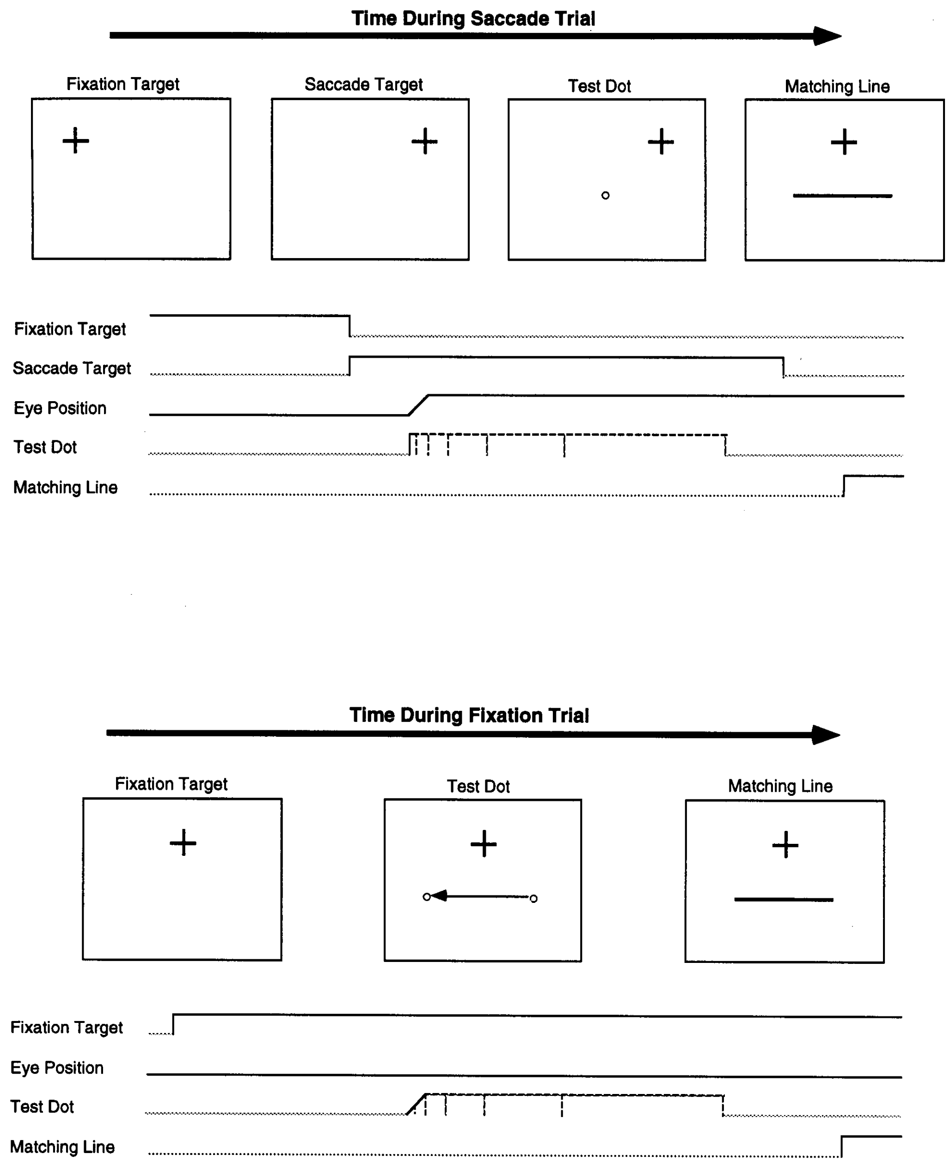

Fig. 1. Schematic illustration of the sequence of events during trials in the saccade (top panel) and fixation (bottom panel) conditions.

1983) that comprised 35 trials, during which the luminance (ΔI) of the dot was varied to achieve 84% correct responses.

Three observers with normal vision participated in the experiments, after first granting voluntary informed consent. Naive observers TN and VS are close to emmetropic in the tested right eye and did not require refractive correction. Author JY wore a spectacle correction of -1.25 -0.25×107 in the right eye. Partial data were obtained also for author HB, which confirmed the results of the three principal observers. The results reported represent averages over at least ten estimates of perceived smear for each target duration in the saccade condition and over at least five estimates of perceived smear for each duration in the fixation condition. Fewer estimates of perceived smear were collected

Table 1
Log relative detection thresholds (± 1 S.E.) for 10 ms targets in the saccade and fixation conditions

Subject	Saccade	Fixation		
		50° s^{-1}	100° s^{-1}	200° s^{-1}
JY	-0.06	-0.27	-0.19	-0.05
	± 0.02	± 0.02	± 0.04	± 0.04
TN	-0.29	-0.56	-0.59	-0.30
	± 0.04	± 0.08	± 0.07	± 0.11
VS	-0.02	-0.04	-0.12	$+0.19$
	± 0.05	± 0.17	± 0.12	± 0.00
Average	-0.12	-0.29	-0.22	-0.05
$\pm$ S.E.	± 0.08	± 0.15	± 0.21	± 0.14

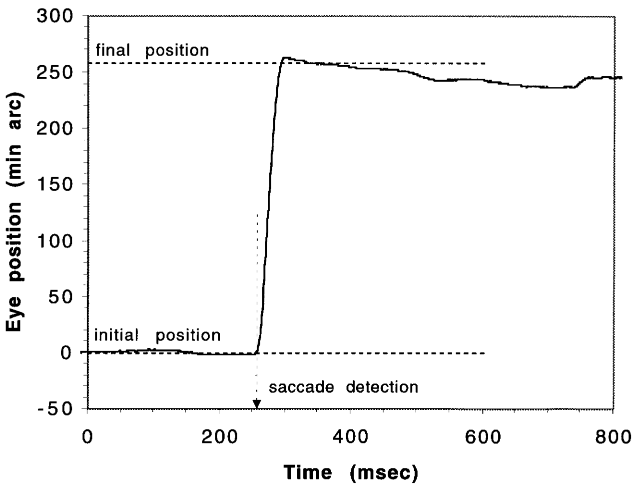

Fig. 2. Horizontal eye position vs. time on a representative saccade trial for observer TN. The extent of retinal image motion during the saccade was determined from the difference between the final and initial eye positions, indicated in the figure by the two horizontal dashed lines. The amplitude of the saccade shown here is 4.3°. As shown by the vertical dashed line, the saccade was detected within a few ms of its onset.

during the fixation condition because the trial-to-trial variability was noticeably smaller.

3. Results

An illustrative trace of horizontal eye position versus time on one saccade trial is shown for observer TN in Fig. 2. For each trial, the initial eye position was determined by averaging the eye positions over a 100 ms interval that culminated 20 ms before the detection of the saccade. The final eye position was determined also by averaging the eye positions over 100 ms, starting 50 ms after detection of the saccade. The mean saccadic amplitude, defined as the difference between the final and initial eye positions, varied among the three observers, being smallest for observer JY and largest for observer VS (see Fig. 3, below). As expected, the duration of saccades covaried with the amplitude, with average values of 28 ± 4, 37 ± 3, and 37 ± 5 ms for observers JY, TN, and VS, respectively. Calculated mean retinal image velocities during saccades were 106, 113 and 124° s^{-1} for JY, TN, and VS, respectively.

In the saccade condition, the extent of perceived smear increases with dot duration up to approximately 20 ms, and then decreases (Fig. 3). The time course of perceived smear does not differ systematically for dots that are 2, 4, and 40 times the contrast detection threshold. Although the time course is similar for all three observers, the magnitudes of perceived smear vary idiosyncratically. Compared with the mean saccadic amplitude, observer JY reported the greatest extent of perceived smear and observer VS reported the smallest.

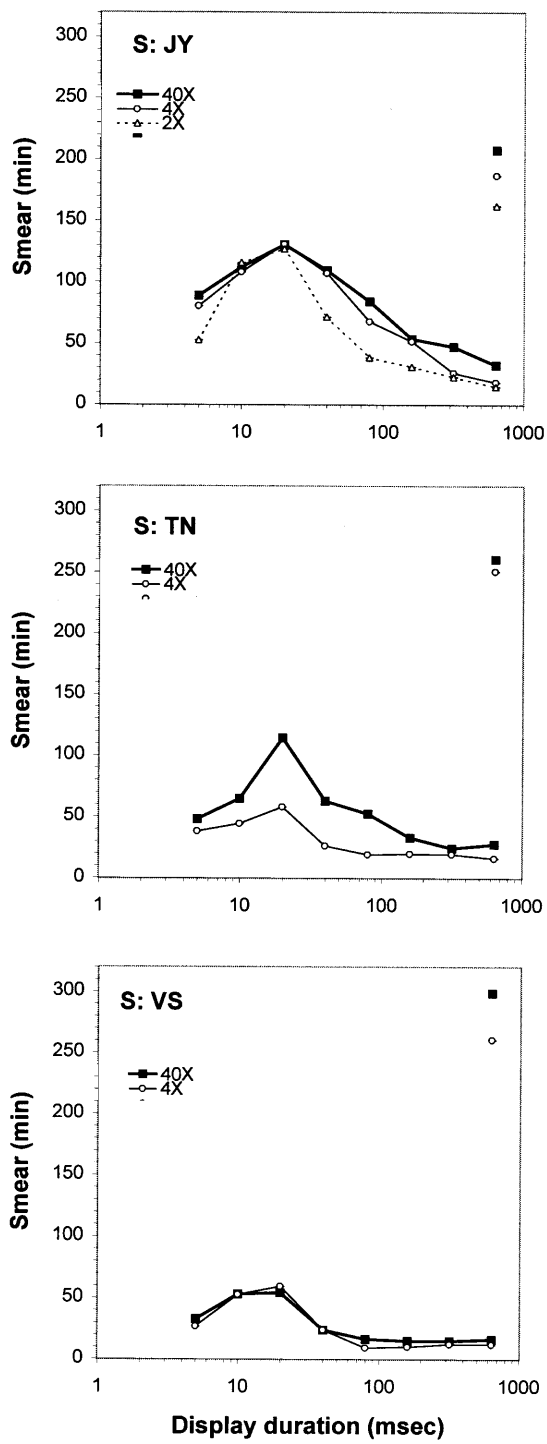

Fig. 3. The extent of perceived smear (in min arc) for a stationary bright dot presented during and for various durations after leftward and rightward saccades. The dot was 40 ×, 4 ×, or (for JY) 2 × its contrast detection threshold. Error bars in this and subsequent figures are ±1 S.E. The isolated symbols at the right of each panel indicate the average magnitude of each observer's saccades for each dot-contrast condition ±1 S.E. Across conditions, the average (±1 S.D.) saccadic amplitudes for JY, TN, and VS were 188 ± 79, 256 ± 49 and 285 ± 79 min arc, respectively.

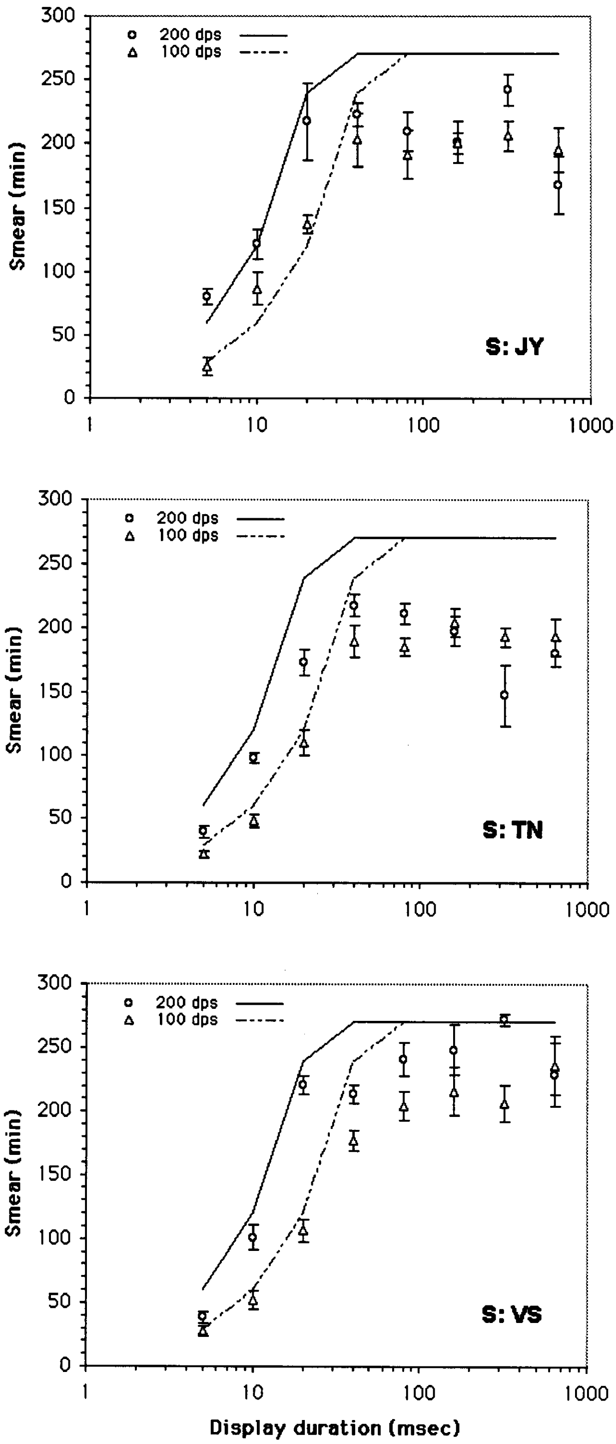

Fig. 4. The extent of perceived smear (in min arc) for a 4 × -threshold bright dot moving at 100 or 200° s^{-1}. For durations longer than 46 ms (at 100° s^{-1}) or 23 ms (at 200° s^{-1}), the dot remained stationary with no change in contrast after it had traversed 4.6°. The thin solid and dashed lines approximate the physical extent of motion vs. duration of the moving dot.

In the fixation condition, the perceived extent of smear increases with dot duration up to approximately 20 ms (200° s^{-1} target velocity) or 40 ms (100° s^{-1} target velocity), and remains essentially constant for longer durations (Fig. 4). All three observers exhibited similar results when the target velocity was 50° s^{-1}, except that the perceived extent of smear increases up to a dot duration of approximately 80 ms (results not shown). These results indicate that the presence of a stationary bright dot at the end of the motion trajectory on long-duration trials produces little masking of perceived motion smear (see also Bedell & Bollenbacher, 1996). We confirmed this result in an auxiliary experiment in which dot contrast increased from 4 × the detection threshold to its maximum value (80–260 × the contrast detection threshold, depending upon the observer) when its motion at 200° s^{-1} ceased. Consequently, a relatively dim *moving* dot was replaced by a brighter *stationary* dot during each long-duration trial. Despite this marked increase in the contrast of the stationary dot, the data of observers TN and VS still reveal little or no evidence for masking of the perceived motion smear (Fig. 5). For observer JY, increasing the contrast of the stationary dot decreased the extent of perceived smear. However, even for observer JY, the extent of perceived motion smear for long target durations is substantially greater in both of the fixation conditions than in the saccade condition (compare the top panels of Figs. 3 and 5).

To ensure that the reduction of perceived smear in the saccade condition could not be attributed to a shift of the background field's image across the retina, subject JY repeated trials from the saccade condition with the background field switched off. Dot luminance was set to 2 × the detection threshold, to minimize visible phosphor persistence. For dot durations longer than 20 ms, the extent of perceived smear was greater in darkness than when the homogeneous background field was present (Fig. 6, compare with Fig. 3, top panel). Nevertheless, without the background field, the extent of perceived smear was still substantially less in the saccade condition than in the fixation condition (see Fig. 4, top panel).

The extent of perceived smear in the saccade condition is shown as a proportion of the perceived smear in the fixation condition in Fig. 7, for dots that are 4 × the contrast detection threshold. To construct these proportions from data on a common scale, the extent of perceived smear was first expressed as a percentage of the dot's retinal image excursion on each type of trial. The retinal image excursion was taken as the angular extent of physical dot motion on fixation trials (dot velocity = 200° s^{-1}) and was estimated from the duration of the target and the mean duration and amplitude of each observer's eye movements on saccade trials. Approximations in estimating the retinal image excursion of the dot when it was presented for only a fraction of the duration of a saccade presumably contribute to the calculated proportions in Fig. 7 that are greater than one (e.g. 5 ms for observers JY and TN, and 10 ms for observer JY). Overall, the proportion of perceived smear on saccade versus fixation trials is greater for author JY than for the naive observers, TN

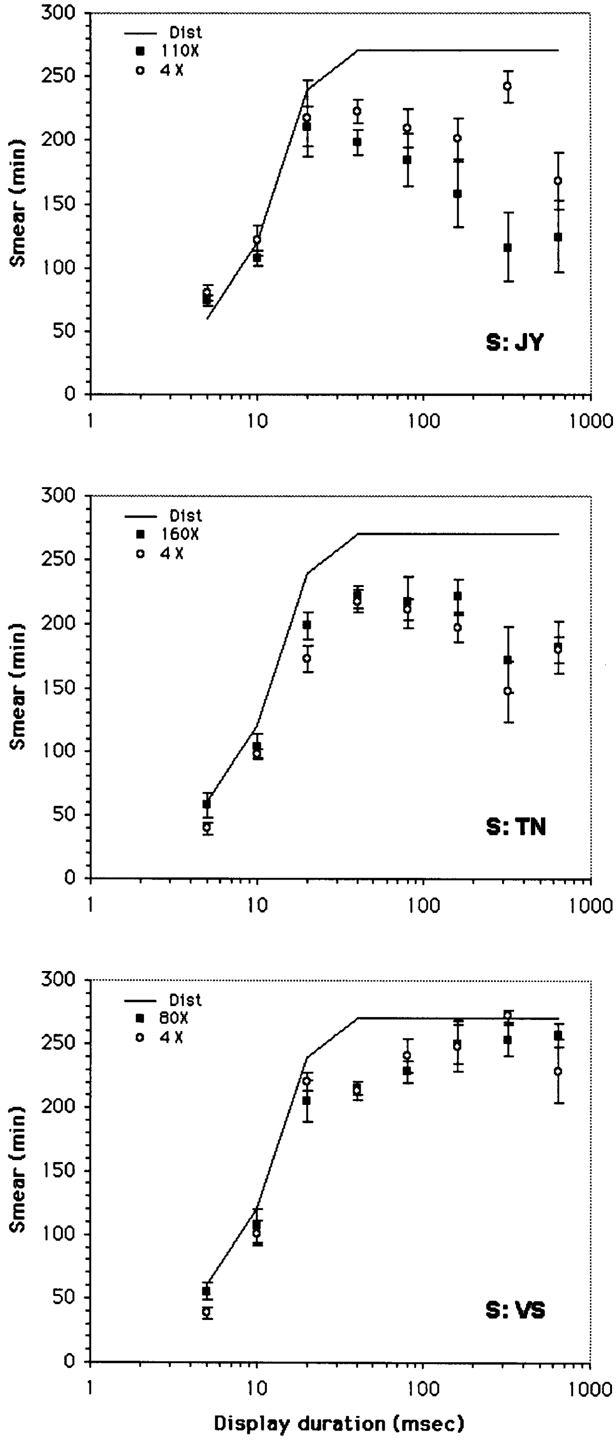

Fig. 5. The extent of perceived smear (in min arc) for a bright dot moving at 200° s^{-1}. Dot contrast was either 4 × threshold throughout each trial, or increased from 4 × to a substantially higher contrast value (JY, 110 × ; TN, 160 × ; VS, 80 ×) when motion of the dot ceased after 23 ms (4.6°). The thin solid line approximates the physical extent of motion vs. duration of the moving dot.

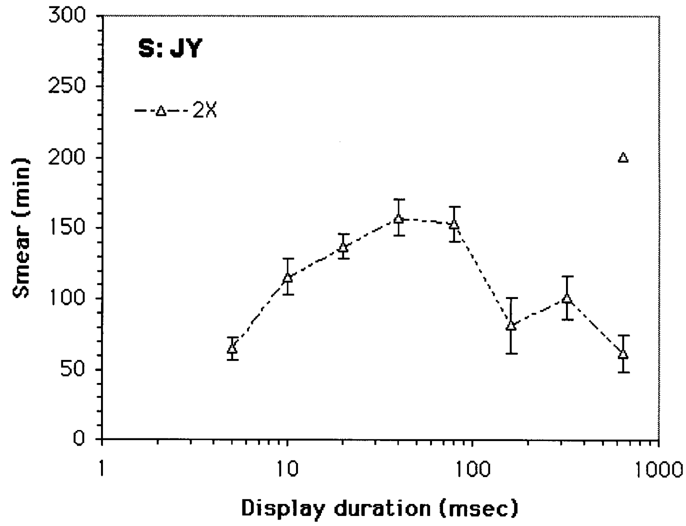

Fig. 6. The extent of perceived smear (in min arc) for a bright dot presented against a dark field, during and for various durations after rightward and leftward saccades. The dot was 2 × the detection threshold. The average saccadic magnitude is shown by the isolated symbol at the right of the figure.

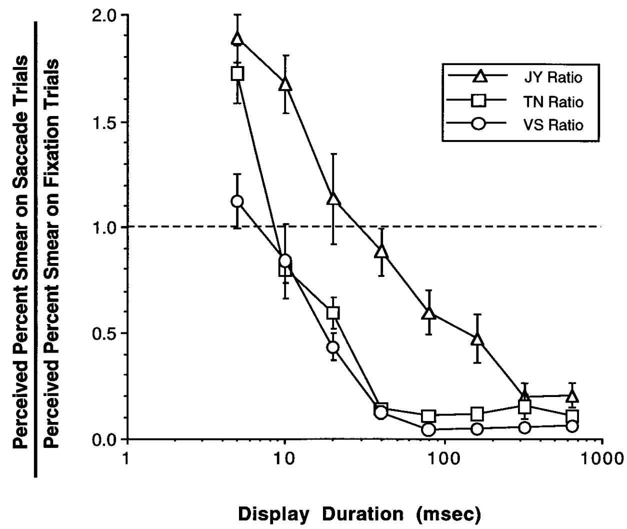

Fig. 7. The proportion of perceived smear compared for dot motion during saccades vs. fixation. Data (from Figs. 3 and 4) are for a target contrast of 4 × threshold; in the fixation condition, the velocity of dot motion was 200° s^{-1}. The extent of perceived smear during saccades and fixation was first expressed as a percentage of the dot's retinal image excursion on each type of trial. Ratios were then computed for each target duration, separately for the three observers. Error bars for each proportion are ± 1 S.E.

and VS. Nevertheless, Fig. 7 shows that all three observers report substantially less perceived smear in the saccade than in the fixation condition for targets of long duration. In particular, note that the proportion of perceived smear during saccades versus fixation is less than 1.0 for a target duration of 40 ms, which is just longer than the duration of the saccadic eye movements in the saccade condition. Consequently, any retinal image motion that resulted from low-velocity eye drift or corrective saccades that followed the primary saccade on some trials (Fig. 1) is unlikely to have contributed to the attenuation of perceived motion smear.

4. Discussion

The decrease in perceived image smear we found for targets that remain visible after the completion of a saccade agrees qualitatively with the results of Matin et al. (1972). However, Matin et al. reported that the extent of perceived smear varied reciprocally with the luminance of the flashed target, which they took as evidence that the perception of image smear was attenuated by metacontrast masking. We found no systematic variation in the perception of image smear with target luminance, perhaps because our stimuli were presented against an illuminated background field that maintained a constant level of light adaptation, rather than in darkness. Because a similar attenuation of perceived smear does not occur when motion of the retinal image occurs during steady fixation, it is unlikely that metacontrast masking can account for much of the decrease in perceived image smear during saccades under the conditions of our experiment. However, when observers make eye movements within a cluttered visual field, the perception of motion smear would be expected to be reduced also by spatio–temporal interactions arising from other nearby targets (Farrell, 1984; Di Lollo & Hogben, 1985; Castet, 1994; Chen et al., 1995).

Saccadic suppression describes a reduced sensitivity to stimulus events that occur during a saccade, presumably resulting from an inhibitory influence of extraretinal eye movement signals, and has been suggested as an additional mechanism to alleviate perception of the retinal image smear that occurs during rapid eye movements (Volkmann, 1962). However, an explanation of our results based on reduced sensitivity to targets presented during a saccade is unlikely, for the following reasons. First, saccadic suppression is weak or absent for small or high-spatial frequency targets (Brooks & Fuchs, 1975; Volkmann, Riggs, White, & Moore, 1978; Burr, Morrone, & Ross, 1994), such as the small dot that was presented in our experiments. In our observers, the contrast required to detect this dot target differed only slightly between the saccade condition and the most comparable ($100° \ s^{-1}$) of the three fixation conditions (mean across subjects = 0.10 log units, see Table 1). Second, if the reduction in perceived image smear during saccades were a consequence of saccadic suppression, then a greater extent of smear should be perceived for targets that are more highly detectable. However, as noted above, the extent of perceived smear in the saccade trials was similar for dots that spanned a log unit or more in detectability. And third, when the effect of saccadic suppression was simulated in the fixation condition, by increasing the contrast of the dot just as its motion ended, little or no reduction occurred in the extent of the perceived smear (see Fig. 5). Because a selective increase in the contrast of the stationary dot should make this dot more effective as a masking stimulus (c.f. Breitmeyer, 1984), the results shown in Fig. 5 represent additional evidence that in our experiments the attenuation of perceived smear during saccades does not result primarily from metacontrast masking.

Although the attenuation of motion smear during saccades is unlikely to result from a reduced sensitivity to the target, we nevertheless propose that this attenuation is mediated by an extraretinal signal for the eye movements. An attractive aspect of this proposition is that it can account also for the attenuation of perceived motion smear for physically stationary targets that we documented previously during smooth pursuit (Bedell & Lott, 1996) and, presumably, for the near-absence of perceived image smear in persons with congenital nystagmus (Bedell & Bollenbacher, 1996). However, the mechanism by which extraretinal eye movement signals influence the extent of perceived smear remains unclear. Recently, Ross and coworkers (Ross, Morrone, & Burr, 1997; Morrone, Ross, & Burr, 1997) concluded that the extraretinal signal for saccades is not applied to all regions of visual space uniformly, resulting in an apparent compression of visual space for stimuli presented before, during, or just after a saccadic eye movement (but see Lappe, Awater, & Krekelberg, 2000). The spatial compression described in these papers occurred only for stimuli located at or beyond the saccadic target, and would not be expected to influence the extent of perceived smear for targets such as ours, between the initial fixation locus and the saccadic goal. Previously, Burr and Morrone (1996) reported a quickening of the temporal impulse response during saccades, which they suggested might result from an influence of saccade-related signals on contrast gain control. A more rapid temporal response would be expected to decrease visual persistence, and could thereby attenuate the perception of motion smear. Unfortunately, no clear change in temporal responsiveness has been documented during pursuit eye movements (Murphy, 1978; Flipse, Wildt, Rodenburg, Keemink, & Knol, 1988) or in persons with congenital nystagmus (Waugh & Bedell, 1992). However, Steinman, Levinson, Collewijn, and van der Steen (1985) and Steinman and Levinson (1990) reported that contrast thresholds for medium and high spatial frequency gratings are better than expected on the basis of the average retinal image speed during head movements, which are apparently compensated incompletely by the vestibulo-ocular reflex (VOR). One possible explanation for their results is that extraretinal signals associated with the VOR increase temporal processing speed and reduce the influence of motion smear on contrast thresholds.

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