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Characteristics of saccades and vergence in two kinds of sequential looking tasks

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Abstract

We determined how saccades were used in the experiments described in Epelboim, Steinman, Kowler, Edwards, Pizlo, Erkelens and Collewijn (1995) [*Vision Research*, *35*, 3401–3422], where unrestrained subjects looked at or tapped nearby targets. We report: (i) the size of binocular saccades; (ii) how well saccade size matched in the two eyes; and (iii) saccadic vergence. A representative sample (3375 saccades) was measured: 83% were $<15°$, 53% were $<5°$. Only two were 'microsaccades'. Saccade sizes were very similar in the two eyes. These results imply that subjects prefer avoiding large saccades. They can do this simply by re-orienting the head appropriately. Subjects under-verged by 25–35% and preformed well. None experienced diplopia.

Keywords: Saccade; Vergence; Saccade symmetry; Vergence distance; Vergence angle

1. Introduction

Saccades, the voluntary, rapid eye movements used to shift gaze, have a wide dynamic range. They can be as small as 5′ and as large as 100° with peak velocities ranging from 3 to 600 deg/s. Even the smallest saccades ($<12'$), called 'microsaccades', are under voluntary control (Haddad & Steinman, 1973; Steinman, Haddad, Skavenski & Wyman, 1973). How are saccades, which can vary by two log units with respect to both size and speed, used in everyday life? The first, and only, attempt to answer this question known to the authors was made by Bahill, Adler and Stark (1975), who reported that "most naturally occurring human saccades have magnitudes of 15° or less" (p. 468). For these authors 'naturally occurring saccades' referred to saccades human subjects made as they walked around the campus of the University of California at Berkeley. Note that they measured saccades with respect to the head, which means that there was no way of knowing the extent to which head movements were used to shift gaze, eliminating a need to make large saccades. Also, note that "microsaccades were omitted since the noise inherent in the EOG technique made it difficult to measure saccades of one degree or less" (p. 468).

Interest in the control of gaze during natural tasks has increased recently, but the contribution of saccades to gaze-shifts has not been treated quantitatively in this work. For example, Land, Mennie and Rusted (1998) used a head-mounted video camera to observe the approximate direction of gaze as subjects made a cup of tea, and when they constructed a peanut butter sandwich (Hayhoe & Land, 1999). Both reports emphasized the temporal relationship between where one looked and what one did. Steinman, Epelboim, Forofonova and Bogacz (1998) used the Maryland Revolving Field Monitor (MRFM) to make accurate measurements of binocular gaze control while a subject performed tasks drawn from the everyday life of human beings and their ancestors, viz., use a stick to pick honey out of a comb, cut meat with a stone knife, fashion an obsidian arrowhead and assemble a Barbie doll from component parts.

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This report emphasized the control of vergence and the accuracy of cyclopean gaze under natural conditions. The nature of saccades, as such, was not described.

The present paper begins to fill this gap. It describes: (i) the size of binocular saccades; (ii) how well saccades size matched in the two eyes; and (iii) saccadic vergence under naturalistic conditions.

2. Methods

2.1. Database

This paper reports the results of additional analyses of data collected with the Maryland Revolving Field Monitor (MRFM) that led to three publications, viz., Epelboim, Steinman, Kowler, Edwards, Pizlo, Erkelens et al. (1995), Epelboim, Steinman, Kowler, Edwards, Pizlo, Erkelens et al. (1997) and Epelboim (1998). These publications dealt with the control of gaze (the line-of-sight in spatial coordinates). They described: (i) visual search, gaze-shift accuracy and the function of gaze-shifts; (ii) gaze-shift dynamics; and (iii) gaze and retinal-image-stability in two kinds of sequential looking tasks performed under naturalistic conditions. Tasks were naturalistic in the sense that the head and torso were free to move.

2.2. Sampling procedure

A representative sample of binocular eye/head movement trials described in Epelboim et al. (1995) was analyzed. Trials were randomly-sampled within subjects (four), tasks (two), number of targets (three) and replications (ten). The two tasks were: (i) look at a sequence of 2, 4 or 6 targets (LOOK) or (ii) tap a similar sequence (TAP). The angular separation of targets was random, varying between about 1.5° and 35° of visual angle. The distance from the subjects' eyes to the targets varied from about 50 to 90 cm, depending on where the targets were and how much each seated subject moved.

2.3. Apparatus

The MRFM, which records binocular gaze accurately with the head and torso free, was described in Edwards, Pizlo, Erkelens, Collewijn, Epelboim, Kowler et al. (1994) and summarized in the papers just cited. Only specifications will be provided. The MRFM consists of three subsystems: (1) A revolving-magnetic-field monitor/sensor coil subsystem using phase-detection to measure angular eye and head positions (angle precision = 1′, linearity = 0.01%). Data were acquired at 976 Hz, successive sample-pairs averaged and stored at 488 Hz. Cube-surface field coils (2.14 m on a side), produced a spatially homogeneous magnetic field throughout a large fraction (~ 1 m^3) of the cube's volume. SKALAR-DELFT sensor-coils measured horizontal and vertical eye-angles. Head roll-, pitch- and yaw-angles were measured with two orthogonal coils mounted on the head with velcro straps. (2) A sparker tracking subsystem measured 3-D translations of the head by detecting the arrival time of acoustic signals generated by a 'sparker' mounted on the head: Translation precision = 0.2 mm, accuracy ~ 1 mm. (3) A worktable (91 cm wide × 67 cm deep × 72 cm high) provided a platform for the targets. Its surface contained an 11 × 14 grid of 154 wells separated by 4.5 cm. Rods, inserted into these wells, were topped with different colored LEDs that served as targets. Targets were turned on before the trial began, and remained stationary and visible throughout the trial in a well illuminated room.

2.4. Calibrations

The phase-detection principle used in the MRFM allows absolute calibration of angles. Two calibrations were performed at the start of each session with the head in a known position on a biteboard to determine the zero-reference for each sensor coil because their position varies across sessions. Each sensor-coils' orientation, relative to the line-of-sight, was determined when the subject fixated each eye's pupil (seen monocularly) in a mirror parallel to the back edge of the worktable. The head coils' zero-references were determined when the XYZ head-position was indicated by the sparker with the head on a biteboard. Two additional calibrations were performed once: (i) sparkers of different heights, placed in 18 locations on the worktable, calibrated 'sparker-space' and (ii) the sighting-centers of each subject's eyes were measured psychophysically with the head on a bite-board.

2.5. Saccade measurement and analysis

Saccades were detected manually with a mouse on a graphic display of the data. Why? We anticipated measuring saccade amplitudes ranging from 5′ to 100°. We had saccade-detecting algorithms, but they could not cover the entire range efficiently. With parameters set to detect microsaccades, fast drifts would be flagged. Set for large saccades, microsaccades would be missed. Once the range of saccade sizes and peak velocities is large, visual inspection of all of the algorithm's detections becomes necessary. We chose to sample representative trials, rather than use the algorithm on all records, and then be forced to separate wheat from chaff by visual inspection.

Saccades were detected by three experienced individuals, all using the same criteria for estimating the onset and offset of the saccades. These criteria were estab-

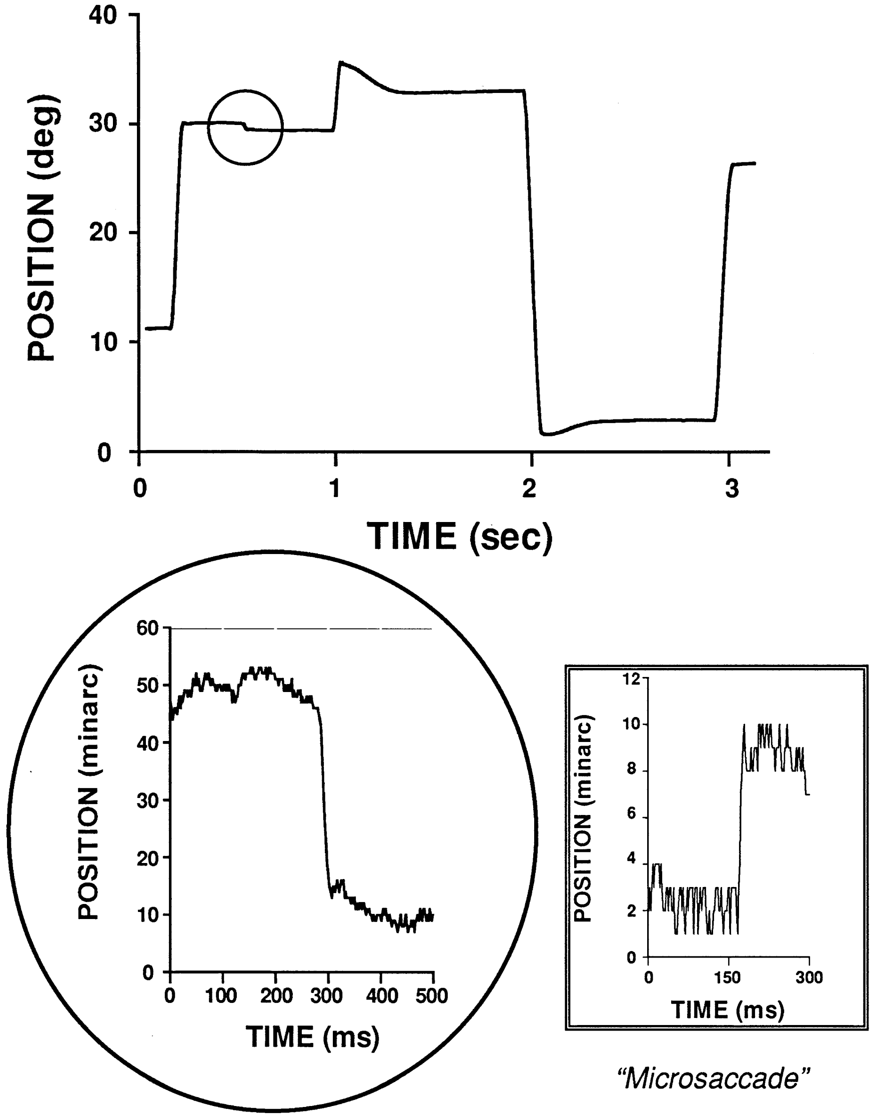

Fig. 1. Examples of saccades of various sizes as recorded with the MRFM. Top: A representative 3 s interval in an eye movement record. It shows the POSITION of the right eye on the horizontal meridian as a function of TIME. Four large saccades can be seen. The first, 0.2 s into the record was about 18°, the second, one second into the record, was about 6°, the third, 2 s into the record was about 32°, and the last, about 3 s into the record, was about 25°. The smaller saccade circled about 0.5 s into the record is shown magnified on the bottom left. It was about 31′. One of the two microsaccades found in our sample is shown on the bottom right, where the POSITION of one eye on the vertical meridian is plotted against TIME. The vertical component of this microsaccade was about 7′. It is clearly visible against the $\pm 1'$ bit-noise-level of the recording instrument.

lished by working together on a subset of trials until consensus was achieved. In all, 3375 saccades were found in the 768 trials sampled. Saccades, as they appear in our records, are shown in Fig. 1.

Saccades were measured with respect to the head. The eye-in-head angles (orientation of the eye with respect to the head) was defined by the Helmholtz coordinate system (see Hallett, 1986, p. 10-5). The coordinate axes of the Helmholtz system, defined during the mirror trials, were fixed to the head as it moved. Saccade size (offset–onset) was analyzed separately for horizontal and vertical meridians because this distinction is meaningful with respect to the oculomotor plant when saccades are measured relative to the head. These meridians lose significance when the head is free and eye movements are measured with respect to space (gaze). Horizontal and vertical vergence angles were computed by subtracting the angles of the right eye from the angles of the left eye at saccade onset and offset. Since the direction of the lines-of-sight on the vertical meridian was of no interest for vertical vergence analysis, the absolute values of the vergence angles were used.

Vergence distance was also analyzed. This analysis was done in spatial, rather than in Helmholtz coordinates. Distance is defined as the Euclidean distance in

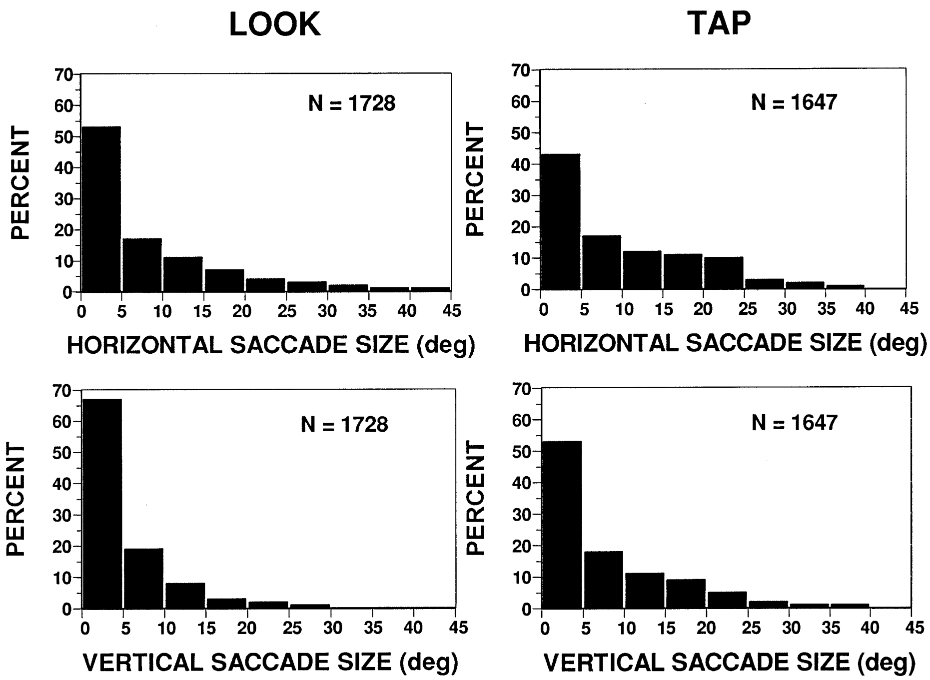

Fig. 2. Relative SACCADE SIZE distribution of all saccades sampled on the HORIZONTAL (top) and VERTICAL (bottom) meridians under the LOOK (left) and TAP (right) conditions. HORIZONTAL and VERTICAL were measured with respect to the subject's head, i.e. in Helmholtz coordinates. The data of all four subjects were pooled.

the 3-D space from the middle of the line connecting the sighting centers of the subject's eyes (baseline) to the 'binocular-gaze point', i.e. the midpoint of the line that joins a point on the right and left eyes' lines-of-sight such that the distance between these two points is smaller than for any other pair of such points.

Note, that had the distance been measured in 2-D, as is customary in most binocular research with the head fixed, the lines-of-sight would have intersected on a plane. We, however, measured the distance in 3-D with the head free. In this condition the lines-of-sight do not have to and actually only rarely actually intersect on a plane.

Vergence distance was computed for each saccade's onset and offset. Target distance was computed as the Euclidean distance from the middle of the subject's baseline to the nearest target nearest to the binocular-gaze point.

3. Results[1]

Data of all four subjects were pooled because no important individual differences with respect to saccade sizes and saccade symmetry were observed. The individual distributions of saccade sizes were very similar to the pooled distributions shown in Fig. 2.

[1] Some of these findings were described at the annual meeting of the Association for Research in Vision and Ophthalmology at Fort Lauderdale, Florida, May 1999.

3.1. Saccade size

Most saccades (83%) were smaller than 15°; the majority (53%) were smaller than 5°. Fig. 3 shows that more than 60% of the saccades smaller than 5° were smaller than 2°. Fig. 4 shows that below 1°, most saccades were relatively large, larger than 0.5°. Only two of the 3375 saccades measured qualified as 'microsaccades' (0.06%), i.e. their 2-D sizes were smaller than 12′. Both microsaccades were made in the LOOK task, one by ZP, the other by CE.

3.2. Saccade symmetry

Fig. 5 (scatter diagrams of left eye saccade sizes plotted against right eye saccade sizes) shows that data points clustered along the line with slope = 1, indicating a high degree of symmetry and a very high correlation of saccade sizes in both eyes. All Pearson product-moment correlation coefficients were at or above 0.986. This was not surprising, because target distance was very much larger than interpupillary distance (see Erkelens, Steinman & Collewijn, 1988, for the conditions needed to produce large asymmetries).

Dispersion around the line of symmetry was higher in the TAP task, perhaps not surprising because all subjects moved their heads and torsos much more in this task, reducing the target distance. The actual performance of these subjects in these experiments can be visualized by going to the webpage at http://brissweb.umd.edu where movements of the body, as well as the eye, can be seen.

3.3. Vergence

Data from each subject will be reported separately. Their performances were similar, but we were surprised by what they did. This encouraged us to show the vergence-setting each subject preferred to use in each task. Vergence angles are shown in Table 1.

In the LOOK task, subjects' mean vergence angles were 3.5°, 3.2°, 4.1° and 3.8° on the horizontal meridian and 0.5°, 1.0°, 0.6° and 0.8° on the vertical meridian for CE, HC, RS and ZP, respectively. Their standard deviations were 0.85°, 0.95°, 1.30°, 1.40° and 0.62°, 0.76°, 0.42°, 0.8°, respectively. In the TAP task, subjects' mean vergence angles were 4.7°, 3.3°, 5.4° and 4.6° on the horizontal meridian and 0.7°, 1.8°, 1.1° and 1.1° on the vertical meridian. Their standard deviations were 1.10°, 1.60°, 1.29°, 1.78° and 0.56°, 1.80°, 0.72°, 0.82°, respectively. All subjects' horizontal and vertical vergence angles were larger in the TAP task than in the LOOK task. The physical distance from the subjects' eyes to the targets in the experimental setup could vary from about 50 to 90 in the LOOK task cm, which corresponds to a range of 7.8°–4.3° of the estimated vergence angles, and from 50 to 75 cm (7.8°–5.2° of the estimated vergence angles) in the TAP task. All subjects

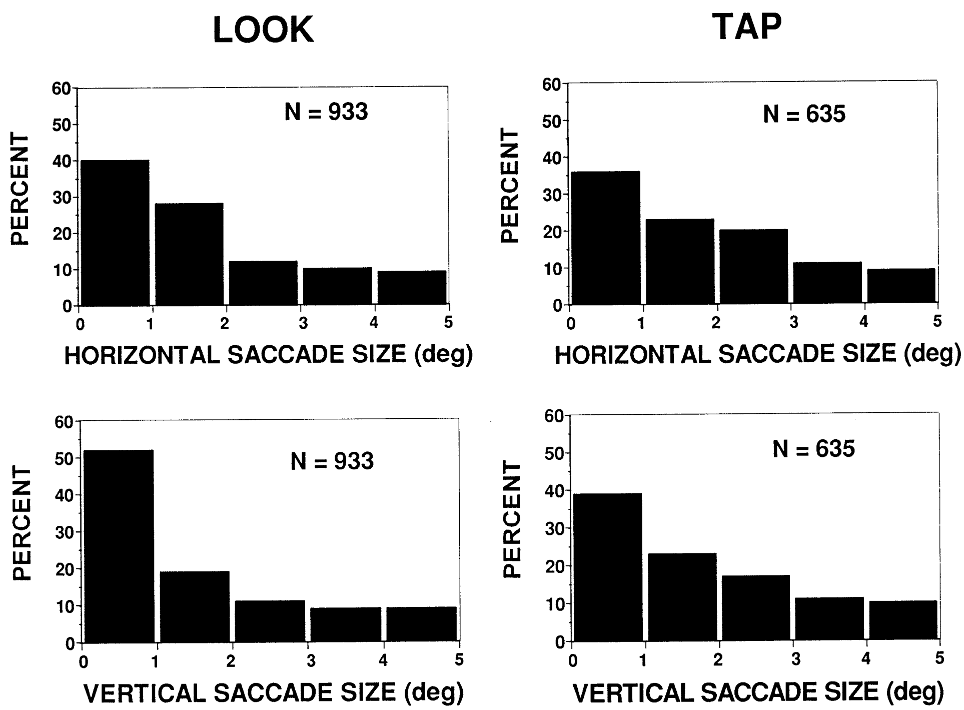

Fig. 3. Relative SACCADE SIZE distribution of all saccades less than 5°. See Fig. 2 for other details.

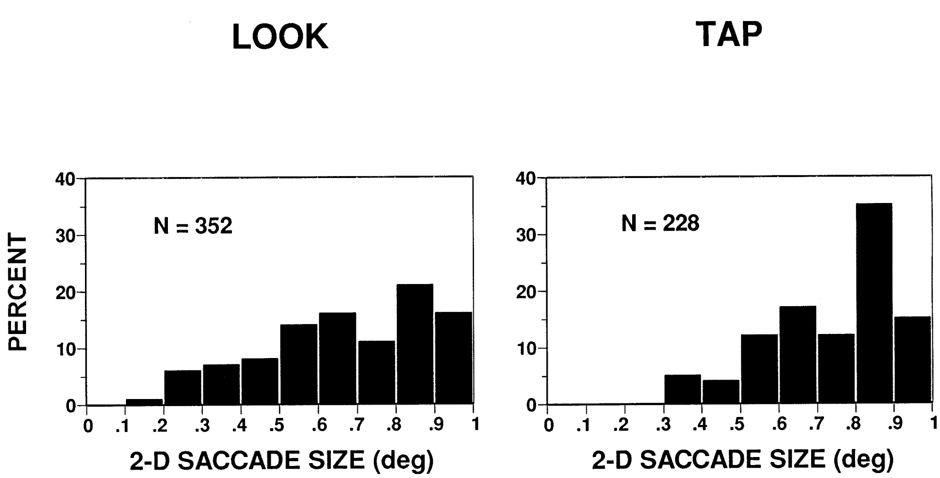

Fig. 4. Relative 2-D SACCADE SIZE distribution for the saccades less than 1° under the LOOK (left) and TAP (right) conditions.

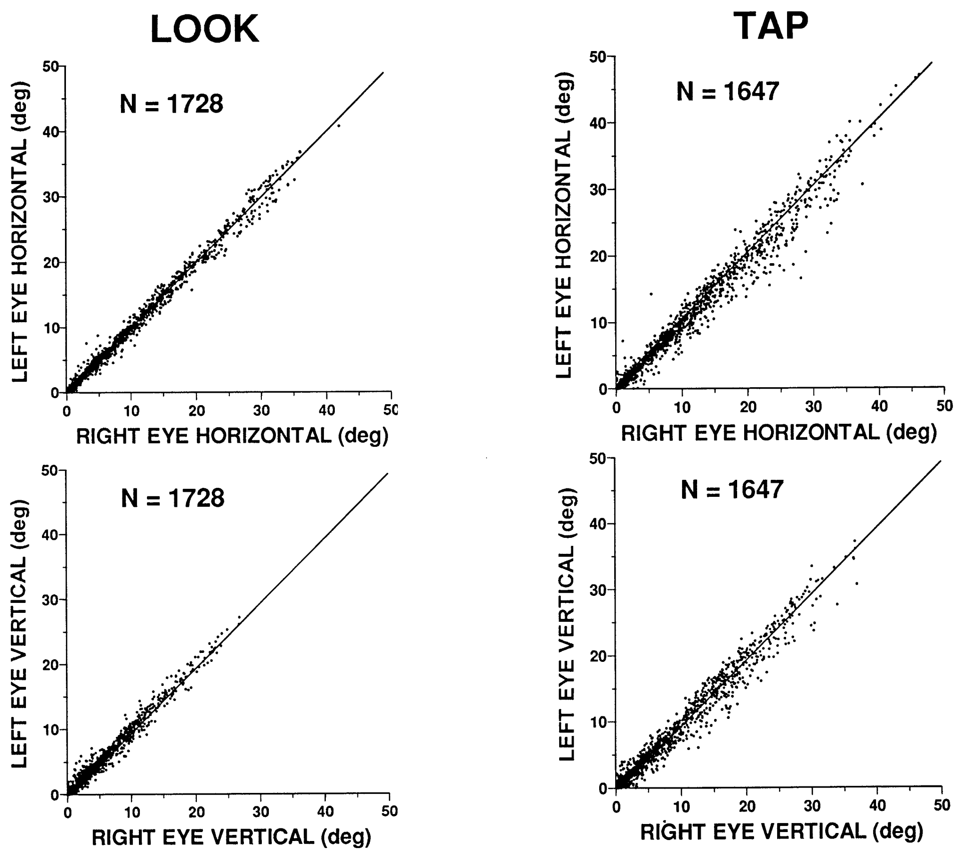

Fig. 5. Scatter diagram of saccade sizes of the RIGHT EYE versus the LEFT EYE on the HORIZONTAL (top) and VERTICAL (bottom) meridians under the LOOK (left) and TAP (right) conditions. Data fall on the straight line with slope = 1 when saccades in both eyes are equal in size.

Table 1
Mean horizontal and vertical eye vergence angles, vergence and target distances[a]

		CE		HC		RS		ZP	
LOOK	*Vergence angles (°)*								
	Horizontal	3.5	(0.85)	3.2	(0.95)	4.1	(1.30)	3.8	(1.40)
	Vertical	0.5	(0.62)	1.0	(0.76)	0.6	(0.42)	0.8	(0.67)
	Vergence distance (cm)	105.2	(25.45)	103.8	(29.23)	97.6	(24.35)	97.4	(33.02)
	Target distance (cm)	69.8	(15.3)	65.4	(16.11)	66.2	(13.56)	67.7	(18.16)
	Difference (%)	34		37		32		30	
	Sample size	691		729		757		801	
TAP	*Vergence angles (°)*								
	Horizontal	4.7	(1.10)	3.3	(1.60)	5.4	(1.29)	4.6	(1.78)
	Vertical	0.7	(0.56)	1.8	(1.80)	1.1	(0.72)	1.1	(0.82)
	Vergence distance (cm)	77.7	(17.34)	75.2	(36.21)	71.0	(17.04)	83.4	(33.41)
	Target distance (cm)	57.1	(12.0)	58.4	(14.51)	55.6	(12.05)	49.1	(16.82)
	Difference (%)	27		22		22		41	
	Sample size	907		594		693		707	

[a] An ANOVA was performed on the means of the vergence and target distances in the two tasks: LOOK: CE: $F = 1597.8$, df = 1381; HC: $F = 1693.1$, df = 1457; RS: $F = 1239.8$, df = 1513; ZP: $F = 859.7$, df = 1601; TAP: CE: $F = 912.2$, df = 1813; HC: $F = 130.2$, df = 1187; RS: $F = 401.6$, df = 1385; ZP: $F = 1228.1$, df = 1473. A MANOVA was also performed on the difference between the tasks: Wilks' Lambda: $F = 621.4$, df = 8. All differences were statistically significant at $P < 0.0001$.

under-verged in both tasks, and the variability of their vergence angles was similar to the variability of the target distances, i.e. ± 2 SD of the horizontal vergence angles in both tasks was comparable to the range of the target distances expressed as vergence angles, about 2.5°–3.5°.

Another way of looking at these results is in terms of vergence distance, i.e. the distance from the center of the line connecting the eyes' sighting centers to the midpoint of the line connecting the two closest points on the eyes' lines-of-sight (see Section 2). Occasionally, subjects looked up and far away from any of the targets on the worktable during a trial. Such saccades, whose vergence distances were larger than 180 cm (twice the working distance), were excluded (2.8%) from the analysis of vergence distance.

All subjects under-verged, i.e. they converged beyond the targets. In the LOOK task, subjects CE, HC, RS and ZP under-verged by 34, 37, 32 and 30%, respectively. In the TAP task, they under-verged by 27, 22, 22 and 41%. This was true both when we look at vergence angles in head coordinates and at vergence distances in spatial coordinates. Furthermore, vergence angles and distances depended on the task. Vergence was set farther in the LOOK task, hardly surprising because all of the subjects tended to sit back in the LOOK task and moved forward when they tapped (this can be seen by going to webpage http://brissweb.umd.edu).

4. Discussion

We examined saccades made under conditions similar to everyday life. Previously, Bahill et al. (1975) made a similar attempt, reporting that most saccades while walking around out-of-doors were smaller than 15°. This is not surprising because most objects would be well-beyond arms' reach. We examined saccades when subjects manipulated nearby objects, a condition in which large saccades might be common because when one works nearby, angular distances among objects can be large, requiring large saccades to accomplish rapid gaze-shifts. This was not the case. Most saccades (83%) were smaller than 15°; 53% were smaller than 5°.These results show that subjects prefer to avoid making large saccades. They prefer, instead, to re-orient their heads, perhaps the simplest and, most efficient way of reducing the saccade size. An oculomotor preference for efficiency was reported by Epelboim et al. (1995), who showed that subjects tapping targets looked at them no more accurately than required to complete the task rapidly. We also observed high degree of saccade symmetry ($\rho \geq 0.986$). Such symmetry is to be expected when target distance is much larger than interpupillary distance, as it was in our experiments (see Erkelens et al., 1988, for the conditions in which large asymmetries can be predicted from the targets' configuration).

The distribution of saccade sizes was not the only surprise. The range of saccadic vergence was also unexpected. Namely, all subjects preferred to under-verge in both tasks, about 25% in TAP and about 35% in LOOK. They kept eyes their converged beyond the 3-D targets. Despite this they performed the tasks well, and did not experience diplopia. Recently, Epelboim, Logvinenko and Steinman (1999) made a similar observation when they found that the wallpaper illusion persisted when large saccadic vergence movements were made.

We have another reportable, albeit expected, result. Namely, microsaccades were exceedingly unlikely. Only two were found in the 3375 saccades measured. Those, who have studied human eye movements under natural conditions with instrumentation sufficiently sensitive (noise $\leq 2'$) to measure microsaccades, have rarely seen microsaccades (Steinman & Collewijn, 1980, were probably the first). But, as far as we know, the actual likelihood of finding a microsaccade under natural conditions has never been reported, in part because: (i) other issues were under study; and (ii) microsaccades had lost their significance by 1980. They were laboratory curiosities, confined to human adults, whose heads were supported artificially. Microsaccades were studied extensively beginning in 1950. By 1980, microsaccades were no longer interesting (see Kowler & Steinman, 1980, for the microsaccade controversy and Steinman & Levinson, 1990, for the role of eye movements in the detection of details between 1866 and1990).

So, why did we go to the trouble of detecting microsaccades once we knew that they were not important and would be rare? We hoped that providing a quantitative description of their actual frequency under naturalistic conditions would encourage oculomotorists to take their presence in data collected with the head stabilized no more seriously than their prevalence in the real world deserved.

4.1. Remaining questions

Two questions remain; one needs an answer, the other seemed not worth the effort required to answer it. The latter will be discussed first; namely, how much did the slow component of vergence contribute under our naturalistic conditions? We reported only the saccadic component because it was obvious in our records that saccades were the primary means of establishing and changing vergence. The slow component after each saccade was not measured simply because the post-saccadic smooth eye movements were neither large nor systematic.

The answer to the first question requires new experiments. Namely, under what naturalistic conditions, if any, do subjects set vergence very close to the distance of the targets, or, more generally, what about the purpose or nature of a given task determines the preferred vergence settings? For example, could subjects be encouraged to set vergence to the actual distance of the targets if stereoacuity was required? An affirmative answer to this kind of empirical question seems likely on the basis of conventional wisdom. But, caution is warranted here. Based on what we have seen so far "Little is known about how vision and eye movements act under ecologically-valid conditions. What we have learned under analytically pure, impoverished conditions, seems not to apply to the real world" (Steinman et al., 1998, p. S457).

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