



The joint contributions of saccades and ocular drift to repeated ocular fixations

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Abstract

We measured the joint contributions of different sized saccades and ocular drift to overall performance in an alternating fixation task. Subjects repeatedly shifted fixation between the centres of a pair of bars of width 2°–2 arc min, either mentally selected or electronically cut from a stationary sine grating display. Eye movement patterns exhibited consistent features across all displays, and pairs of widely separated bars were studied most. Variability (S.D.) and relative accuracy (under/overshooting bias) were estimated from the concentration of eye positions over the two target bars. Overall variability, i.e. for eye movements as a whole, reached a minimum of 5 min for bar widths less than 20 min across subjects, displays and tasks. This was consistent, as were several other aspects of the study, with a constant 20-min diameter goal zone hypothesis. For wide bars, overall variability increased nearly as the square root of bar width, and for narrow bars, was independent of bar separation. A typical between-bar crossing saccade was tightly constrained in departure point but widely scattered in landing position, the associated variability increasing with bar separation. The final high overall precision was achieved largely by within-bar saccades of greater than 7.5 min effective amplitude that were present at a rate of 1 (range 0.3–3) per crossing saccade. This is consistent with views that very small saccades (the smaller microsaccades) make little obvious contribution to oculomotor performance. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

When comparing fine detail at different spatial locations, large ‘crossing saccades’ shift ocular fixation between the two samples, while smaller saccades and ocular drift shift fixation within a sample (Bozkov, Bohdanecky, & Radil, 1984). Several significant studies of oculomotor control have relatively little to say about the *joint* contributions of the different sizes of saccade and ocular drift in this real life task. Progress in those studies depended on separating saccades from drift, e.g. long single fixations on very small targets (e.g. Stein-

man, 1965; Steinman, Cunitz, Timberlake, & Herman, 1967; St. Cyr & Fender, 1969; Steinman, Haddad, Skavenski, & Wyman, 1973; de Bie & van den Brink, 1986; Ott, Seidman, & Leigh, 1992), or end-saccadic errors for randomly-stepped targets (e.g. Hallett, 1978; Deubel, Wolf, & Hauske, 1986; Lemij & Collewijn, 1989; Kowler & Blaser, 1995). There are several issues to be addressed if we are to understand the manner in which eye movements affect performance in a visual comparison task. These include the effects of target contrast, target structure and task instructions on oculomotor performance. In the present study, we have chosen to address one aspect of target structure: bar width. With this in mind we have devised a new stimulus display and oculomotor analyses.

We chose the bars in a sine grating as fixation targets because (a) more complex visual stimuli can often be conveniently synthesized from sine gratings (e.g. Hof-

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mann & Hallett, 1993), and (b) sensory responses to sine gratings are very well understood (Schade, 1956; Campbell & Robson, 1968; Blakemore & Campbell, 1969; De Valois et al., 1982), yet (c) only one oculomotor study has examined fixations on sine gratings (Arend & Skavenski, 1979). The effects of perceptual clutter on oculomotor performance with gratings (Kowler & Steinman, 1977) led to our excising most of the bars, restricting the display in the position domain and so increasing the number of frequency channels that might contribute to the precision of fixation. This was fully consistent with our interest in optimal performance¹.

As a method for extracting a measure of oculomotor precision we used the 'dwell time histogram' (St. Cyr & Fender, 1969). A high-resolution scleral coil system recorded the total time spent by the foveolar centre at each position in the display, as fixation shifted to and fro between the two target bars². Typically, the cumulative dwell time is a double peaked histogram, so we characterized the variability of fixation by the standard deviation, σ_{DWELL} , of eye position about each peak. Our dwell-time histogram resembles plots of the distribution of eye position sampled during prolonged fixation (e.g. Steinman, 1965), except that many normal duration fixations are pooled. Consequently, the dwell histogram combines the joint contribution of various sizes of saccade and ocular drift, unless the experimental data are specially filtered to remove specific eye movements.

The terminology in the Results refers to the *overall response* arising from all movements, to *crossing saccades*, and to *within-bar saccades* and *drift*. Microsaccades, if characterized by large initial overshoot or an effective amplitude of about 7.5 min (range 2–28 min, e.g. Hallett, 1986), are the smallest within-bar saccades. Experiment and analysis will support approximately 7.5 min as being a critical size when distinguishing between smaller and larger movements in a fixation task (Section 3.6). The theoretical concept is that an accurately fixated critical task detail lies randomly within a finite retinal 'goal zone' (Hallett, 1986). Such a goal zone limits the achievable ocular precision because the critical task detail may be located at any x , y location within it. If the goal zone were a square of side length 20 min and the eye 'on target', an *insignificant* horizontal component for an eye movement (whether saccade or ocular drift)

¹ The study of more narrowly tuned, near threshold contrast, 'wavelet stimuli' was deferred in case these were suboptimal targets due to the activation of few channels or ambiguous targets because of substructure.

² The foveola is usually defined as the central 1.4° of the retina (e.g. Polyak, 1941).

would have an amplitude of < 10 min because such a movement shifts the goal zone away from the critical task detail, wherever it randomly lies within the zone, with < 50% probability. For a circular goal zone of 20 min diameter the corresponding value is < 7.5 min³. Conversely, when fixation is 'off target', eye movements > 7.5 min make a significant change to what falls within the retinal goal zone, with movements > 20 min completely changing the goal zone content. The analysis will confirm that 7.5 min is the approximate threshold that usefully divides 'insignificant' or error preserving movements from 'significant' or error changing movements⁴.

It is known that the variability of steady fixation on single static targets can be extremely low (e.g. average S.D. = 7 min, Ott et al., 1992), so we had expected the variance in our two-target task to be much higher because of errors added by the large crossing saccades. It turns out that the landing points of the crossing saccades are widely scattered across the bars but, as these movements are relatively brief (only tens of milliseconds), a great deal of the total 40-s trial is spent on drift and within-bar saccades. Thus our new task, despite the frequent relatively large shifts of fixation, proves comparable with prolonged fixation on a single target — and in either the two or one target case it is the within-bar saccades larger than about 7.5 min that do most to reduce any error left by larger saccades or accumulated by smaller ones and drift.

2. General methods

2.1. Apparatus

Subjects were seated in the centre of a magnetic field coil and viewed a CRT (Tektronix 608 with P31 phosphor) from a distance of 57 cm. Head movements were restricted by a dental bite, reducing the effects of translational movement. The sides of the coil frame were covered with thin translucent plastic (10 cd/m²) and a window in the end wall provided a 9.7 × 9.7° view of the CRT face.

³ The statistics of the Lightstone goal zone model for fixations and displacements are derived in Hallett (1986). The goal zone may actually be elliptical (e.g. St. Cyr & Fender, 1969). The old term 'dead zone' is unsuitable because (i) there is continuous movement of the task relevant detail within the zone, and (ii) there is always some probability that an abrupt tiny shift of the fixation target will elicit a restorative saccadic response.

⁴ The error preserving movements may, of course, serve some useful function, such as preserving image visibility.

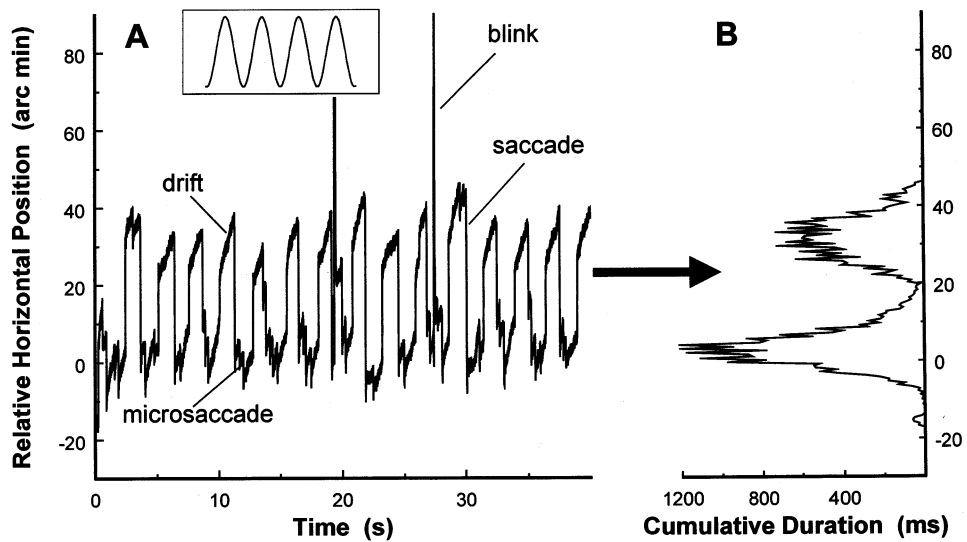


Fig. 1. (A) Typical data obtained for a single trial for subject PEH, sine grating condition (Experiment 1). The task was to fixate alternately the centre pair of bright bars in a sine grating. In this case, the bar width was 20 min (i.e. spatial frequency 1.5 cpd). (B) Dwell-time histograms were created by plotting the total time spent in each horizontal position along the visual pattern. Typical 40-s trial. The S.D. of a fitted double Gaussian were used as estimates of overall variability due to the combined action of all eye movements. Inset shows the luminance profile for the type of stimulus used in this experiment.

2.2. Stimuli

Sine gratings were produced by an Innisfree Picasso image synthesizer under computer control (mean luminance = 48 cd/m², Michelson contrast = 0.55). Luminance and colour were held constant across all experimental conditions. Bar pairs were electronically gated. We restricted the stimulus to vertical gratings or bars and measured only horizontal eye position. Mean luminance, contrast and bar width were always defined as if the full grating were present (e.g. bar width was defined as one half period). Targets were static and predictable. For consistency with grating studies we refer to bar width, though we measured oculomotor precision by standard deviation (S.D.) of a fitted Gaussian distribution to the dwell histogram (see below). To compare these two measures, use S.D. for a cosine bar = 0.36 × bar width.

2.3. Measurement of eye position

A magnetic field oscillated in spatial quadrature at 75 and 100 kHz while eye movements were recorded using contacting scleral search coils (Skalar Medical BV, Delft, The Netherlands; Rempel, 1984). The scleral coil was applied to the left eye and the right eye patched. Eye position was low-pass filtered at 100 Hz (−3 dB) and sampled (250 Hz) with 12-bit precision. When required (Section 3.6), eye velocity was calculated by a four-point algorithm, e.g. a threshold of 5°/s was exceeded when instantaneous velocity exceeded 5°/s for two consecutive pairs of points. A typical 16-point smoothing algorithm (e.g. Tompkins, 1981) attenuates

very short duration (i.e. very small) saccades. The first and last trials of every session calibrated for gain and offset; subjects fixated a display of Maltese crosses, 2.6° diameter and 50% contrast, consisting of four triangular sectors converging to a point.

2.4. Subjects

Authors PEH and SJH were male, aged 59 and 35 years. RYC was male, aged 25 years. All three had visual acuity 6/6 (corrected) in the eye used. PEH was highly practiced in oculomotor tasks, while the others had minimal previous experience. RYC was naive with respect to the purpose of the experiments. None had any history of ophthalmic disorder. Following placement of the coil, the experiment proceeded only if visual acuity exceeded 6/9. This test was repeated before coil removal. Typical in situ acuity was in the range 6/7–6/5 throughout the session. For PEH a spectacle lens (+1.50 D) corrected presbyopia.

2.5. Procedure

Subjects controlled trial onset with a button press which initiated recordings. They alternately fixated a pair of bright bars as accurately as possible until a tone signaled the end of the trial. Alternation of fixation was self-paced. Bar width or position was then adjusted and the next trial initiated. On average, twenty-three 40-s trials were carried out in each 30-min session. Fig. 1 shows typical data obtained for a single trial.

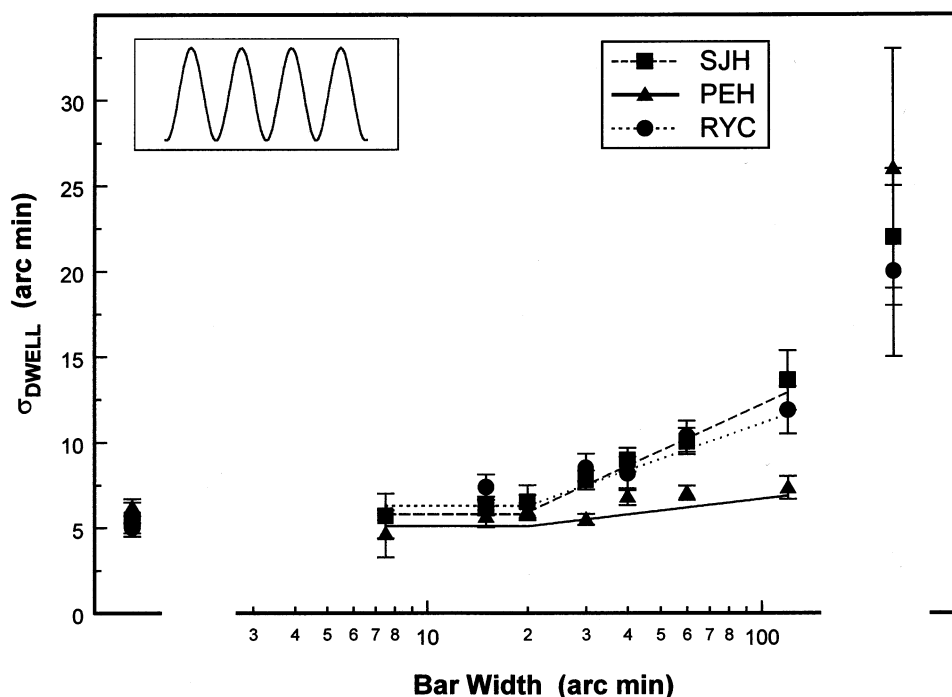


Fig. 2. Overall mean variability of repeated fixations as a function of bar width (i.e. 1/2 period) in Exp. 1 (Sine Grating). Points on the extreme left are results for Maltese crosses (i.e. 'infinitely small bar width'). Points on extreme right are results obtained with no stimulus present (i.e. blank screen; 'infinitely wide bar'). Data for three subjects. Error bars indicate ± 1 S.E. Superimposed lines are best two-line fits, with one line constrained to be horizontal (see text, Section 3.3, for details).

2.6. Dwell-time analysis

Dwell-time histograms were constructed (Fig. 1) for each trial by collapsing eye-position recordings over time, and computing the time spent at each position in the display during the 40-s trial. Estimating variability by the S.D. requires care but two different methods agree: (i) Iterative fitting of two independent Gaussian distributions to the dwell-time plot by a method of rapid descent with all parameters free, minimizes mean square error and the impact of outliers⁵; (ii) It is equally satisfactory to calculate the sample S.D. iteratively, discarding outliers more than 2.5 S.D. from the current mean, until σ_{DWELL} approaches constancy. We estimated undershooting or overshooting 'bias' as the separation of dwell histogram peaks (means) minus bar separation.

3. Results

The first four findings come from experiments that progressively modify a sine grating visual display by

⁵ Manual deletion of individual blinks and saccadic transients offers little as the baseline is always near zero whether the record is filtered or not, because large transients contribute almost no dwell-time at almost all positions—e.g. compare Fig. 1b (unfiltered) versus Fig. 5b (filtered).

excising bars, the second four from experiments that change the subject's instructions or the type of analysis. The usual measures are variability and bias for the overall pattern of eye movements. Filtering the records (Section 3.6) isolates the contributions of the different types of eye movements.

3.1. Clutter in gratings leads to an undershooting strategy

Grating spatial frequency in Exp. 1 (Sine Gratings) varied from 0.25 to 4 cycles per degree (cpd), i.e. 2–38 cycles per display, and the subject mentally selected a pair of adjacent bars as fixation targets. Two subjects (SJH and PEH) showed a pattern of strong unidirectional drift across the target bar (e.g. Fig. 1; Steinman et al., 1973; Murphy, Kowler, & Steinman, 1975; Winterson & Collewijn, 1976), while the third (RYC) showed less consistent drift with some direction reversals and generally more within-bar saccades. Drift amplitude is frequently 10 min during a single intersaccadic fixation pause for the two drifting subjects but closer to the frequently cited value of 2–3 min for RYC (Ditchburn & Foley-Fisher, 1967). The central part of Fig. 2 shows the relation between the precision of repeated fixations and spatial frequency. Overall precision improves with increasing spatial frequency (plotted here as bar width). The supplementary values

at the left and right of Fig. 2 estimate the extreme limits of the possible measuring space. The points at the left are results for Maltese crosses as fixation targets (the centre of a Maltese cross can be regarded as a highly defined target with infinitely small width). Those at the right are for when no stimulus was present and the subject was asked to imagine two separated bars on the uniformly lit CRT (i.e. the complete absence of target structure) and make repeated fixations accordingly. This latter S.D. is five times greater than for a Maltese cross.

For the narrower bars (i.e. high-frequency gratings), subjects reported difficulty in maintaining fixation on any particular pair of adjacent bars. Analysis of individual eye movement records revealed occasional shifts of fixation to a new pair of bright bars despite instructions to alternately fixate a single pair of bars. Relevant data are plotted in Fig. 3, which shows bias as a function of grating bar width. Subjects undershot all except the widest bars by about 10 min. Thus it is possible (and consistent with subjects' reports) that, at the narrower bar widths, subjects were over-controlling their shifts in fixation, and keeping to the inside edges of adjacent bars, so as to reduce the chance of a crossing saccade accidentally jumping over the target bar to an adjacent nontarget bar. Equivalently, and consistent with the goal zone hypothesis, subjects may have attempted to keep the nearest edge region of a 20-min goal zone on the centre of the left or right target bar.

The next experiments simplify the display — and it is noteworthy that the corresponding bias plots show no undershooting, only a near zero bias (range ± 10 min).

3.2. Alternating fixations of adjacent fine details are micro-nystagmic

Given a possible contribution of clutter to the precision of repeated fixations in Exp. 1, Exp. 2 (Isolated Adjacent Bars) used a display in which all but the central pair of grating bars were removed. Fig. 4 shows the same relation between fixation precision and bar width as Fig. 2 of Exp. 1.

An initially surprising finding for all three subjects, much less marked for RYC, was a micro-nystagmus of alternating drift eye movements and saccades, which caused adjacent dwell-time histograms to merge when bars were very close (Fig. 5).

This made it impossible to fit a double-Gaussian function at the smallest bar separations. Micro-nystagmus is not a new discovery as it can be seen in particular subjects in earlier records whether fixating on a small point or two close lines (Yarbus, 1967; Steinman et al., 1973; Ott et al., 1992). The finding of nystagmus to fine bar pairs reinforces the idea that microsaccades are unnecessary in tasks requiring small

amplitude ocular control (cf. Kowler & Steinman, 1980). We incline to the view that drift is goal-directed or position-error sensitive (e.g. Nachmias, 1959; St. Cyr & Fender, 1969; de Bie & van den Brink, 1986) but have no reason here to exclude retinal image velocity as a possible factor in drift or 'slow control' (e.g. Steinman et al., 1973).

We are impressed by the qualitative consistency of oculomotor behaviour across conditions; if one ignores the difference in scale, the major difference between the alternating fixations of Fig. 1 and the micro-nystagmus of Fig. 5 is that the crossing saccades become unidirectional when target details are very close. The subjects are also very similar in overall performance as measured by σ_{DWELL} (Fig. 4). All records for the unidirectionally drifting subjects SJH and PEH consist of a saccade

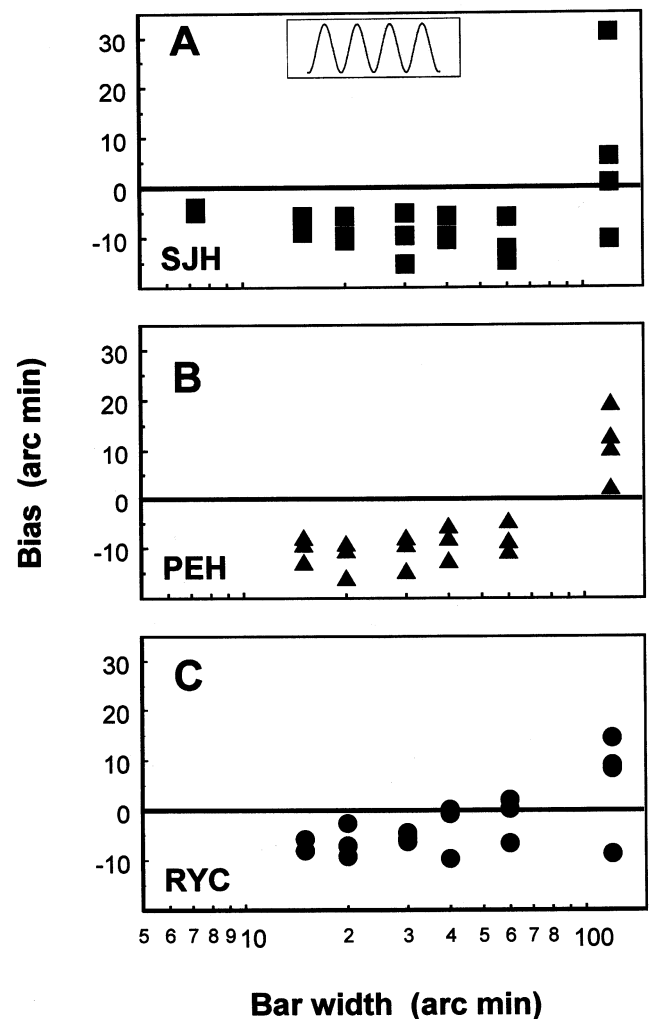


Fig. 3. Bias (i.e. relative accuracy) of repeated fixations plotted against bar width. Bias was defined as the difference between the separation of the targets and the separation of the centres of the dwell histograms. Undershooting results in negative bias, and overshooting in positive bias. Each symbol represents data from individual 40-s trials (i.e. within-trial bias). Except for the widest bars the typical within-trial estimate of the variance in the bias is about 2 arc min².

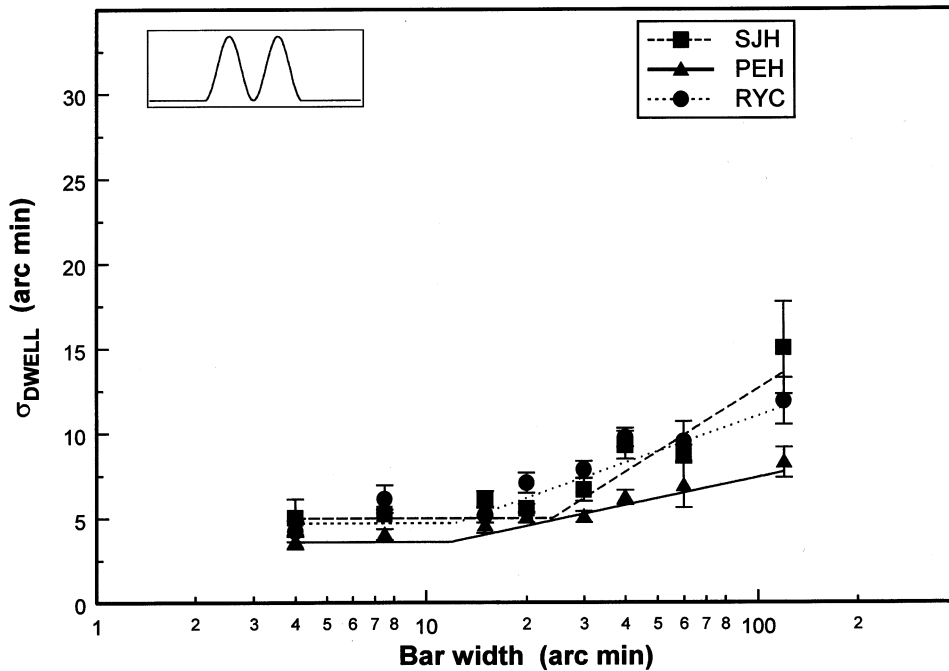


Fig. 4. Overall fixation variability versus bar width in Exp. 2 (Adjacent Bars). Details as in Fig. 2.

followed by unidirectional drift, and possibly a within-bar saccade, plus a final saccade in the same (Exp. 2, Fig. 5) or opposite direction (Exp. 1, 3; Fig. 1) — depending on the display — to restart the process. Subject RYC's drift is less directional and his responses tend to involve nearly twice as many within-bar saccades.

3.3. Overall variability is determined by bar width

Neither Exp. 1 nor Exp. 2 resolved whether overall variability, σ_{DWELL} , is correlated with bar width or bar separation because these two variables covaried in the displays. Exp. 3 meets these difficulties by using a pair of bars at a constant centre-to-centre separation of 4° and a bar width varying from 2° to 2 min. Other details were as previously.

Fig. 6a shows the relation between fixation precision and bar width for bars at a constant separation; the data generally overlap and extend the plots of Fig. 2. The optimal value of 4–6 min is approached asymptotically at bar widths thinner than 20 min (range 10–30 min). It should be noted that a S.D. of 5 min is the prediction for a 20-min goal zone (Hallett, 1986). We have carefully confirmed the two-segment interpretation of these plots by examining single and double line fits to linear, log–log and semi-log empirical plots of all data. Fits for the double line models to semi-log plots were always optimal, though only slightly better than double log fits (typical mean squared error = 2.5 min^2). The slope of the line segment for narrow bars was always close to horizontal, and allowing its slope to

vary did not improve the fits. Parameter means for the double line semi-log fits pooled across subjects were: horizontal segment intercept 5.3 min (range 4.0–5.9 min); unconstrained segment intercept -6.9 min (-7.5 to 0.11 min), slope 9.0 (3.9–9.5). If a double log fit is preferred, the sloping asymptote is close to a square root relation (mean slope of 0.40, range 0.30–0.47).

3.4. Overall variability is independent of bar separation

Exp. 3 was the first indication that precision correlates with bar width (local image structure) and not bar separation. In order to test the hypothesis most vigorously, a fourth experiment was carried out with the distance between the bars varying from 7.5 min to 2° , while bar width remained constant at 2 min. Fig. 6b shows no relation between overall variability (σ_{DWELL}) and bar separation for bars of constant width (2 min). This reinforces the conclusion in Exp. 3 that overall σ_{DWELL} is influenced by the characteristics of the stimulus rather than its location. This effect of bar width owes little to the crossing saccades, as the next experiments show.

3.5. Variability is similar whether fixating one bar or alternating between two

In the experiments described above, subjects used a combination of saccades and drift to alternate fixation between a pair of bars. In Exp. 5, we eliminated large crossing saccades by asking subjects to maintain steady fixation on the centre of a single midline bar for the

entire 40-s trial. Bar width was blocked. Plots are flatter than in Exp. 1–3 but still show the typical worsening in σ_{DWELL} with increased bar width (Fig. 7). This is not surprising as the oculomotor records are comparable to those for Exp. 2 (Isolated Adjacent Bars), showing well developed micro-nystagmus for subjects SJH and PEH, and increased saccadic activity relative to the other subjects for RYC.

A sixth experiment (Repeated Vertical Fixations) eliminated the large crossing saccades another way. Subjects made alternating fixations but now only in the vertical direction, i.e. they repeatedly fixated the centre of a single vertical bar at an approximately constant distance (order $\pm 1^\circ$) above and below the horizontal. Complete data (three sessions) were obtained only for PEH and SJH. Plots (not shown) resemble the data of Exp. 3 (Variable Width Bars of Fixed Separation), with a slightly slower deterioration in performance for the wider bars. This experiment also suggests that the largest (crossing) saccades contribute little to the typical bar width effect. Optimal overall precision was again around 5 min.

3.6. Filtering the records confirms that overall precision is largely determined by saccades of > 7.5 min effective amplitude

The dwell histogram and the two quantities derived from it, variability (σ_{DWELL}) and mean under- or overshooting bias, have so far been *overall* measures for the cumulative effect of all types of eye movement present in the original records. We created new records and new estimates by filtering the original eye position records of Exp. 3 at $5^\circ/\text{s}$ to remove ocular drift (generally < 10 min/s), and then additionally imposed a static

threshold amplitude (range 7.5–60 min) that must be exceeded for a saccade to be registered in the new record.

To compensate for discarded intersaccadic drifts and saccades there was an equivalent instantaneous discontinuity in position at the beginning of the next preserved saccade, so that the filtered record remained accurate in position. Because within-bar saccades often show initial dynamic overshoots, we defined the beginning of a saccade as the time when eye velocity exceeded $5^\circ/\text{s}$ and the end of a saccade by the time when velocity first fell below $5^\circ/\text{s}$ and remained below that threshold for the next 40–100 ms; the static threshold amplitude was measured between these start and end points. We assumed that few or no within-bar saccades, including microsaccades, had peak velocities less than $5^\circ/\text{s}$ (e.g. Hallett, 1986). Microsaccades, which have been characterized as saccades with relatively large initial overshoot and small effective displacement, correspond to our smaller within-bar saccades.

Fig. 8 (A–C) shows σ_{DWELL} for filterings of Exp. 3 data (Variable Width Bars of Fixed Separation). The lowest trace in each panel (thin solid line) represents overall variability in the original record. Variability shows little or no change on the elimination of drift and the smallest within-bar saccades < 7.5 min (trace ii, dotted line, $5^\circ/\text{s} + 7.5$ min threshold), and then increases markedly as many of the remaining within-bar saccades are discounted (trace iii, dashed line, $5^\circ/\text{s} + 15$ min threshold). Finally, extreme filtering leaves just the variability due to the crossing saccades (trace iv, heavy line, $5^\circ/\text{s} + 60$ min threshold). In brief, all movements > 7.5 min are on average precision improving (variability reducing), while those < 7.5 min do not change precision very much.

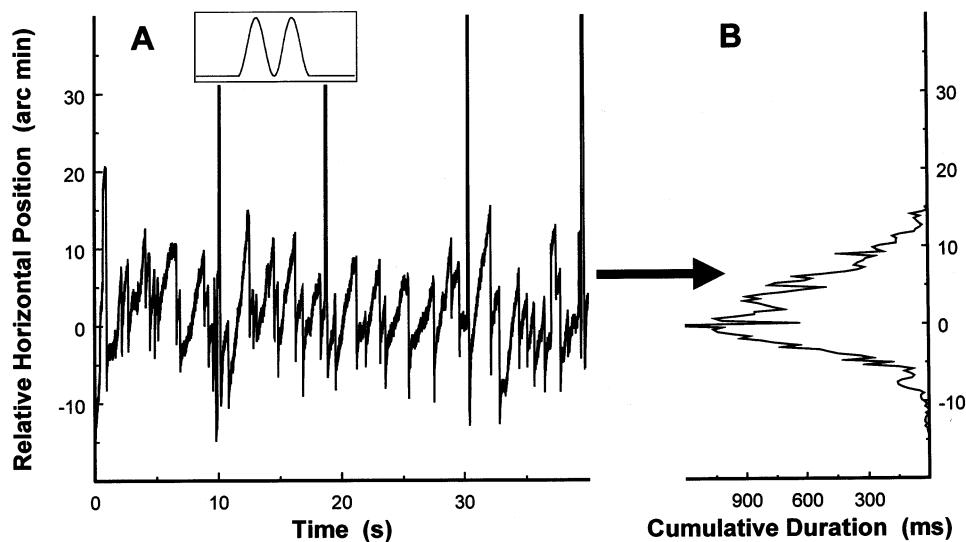


Fig. 5. Typical data obtained for a single trial for subject PEH, extremely narrow close bars, Exp. 2 (Adjacent Bars). Note nystagmus-like pattern of eye movements (A), which resulted in merged dwell-time histograms (B). Equivalent spatial frequency 4.0 cpd.

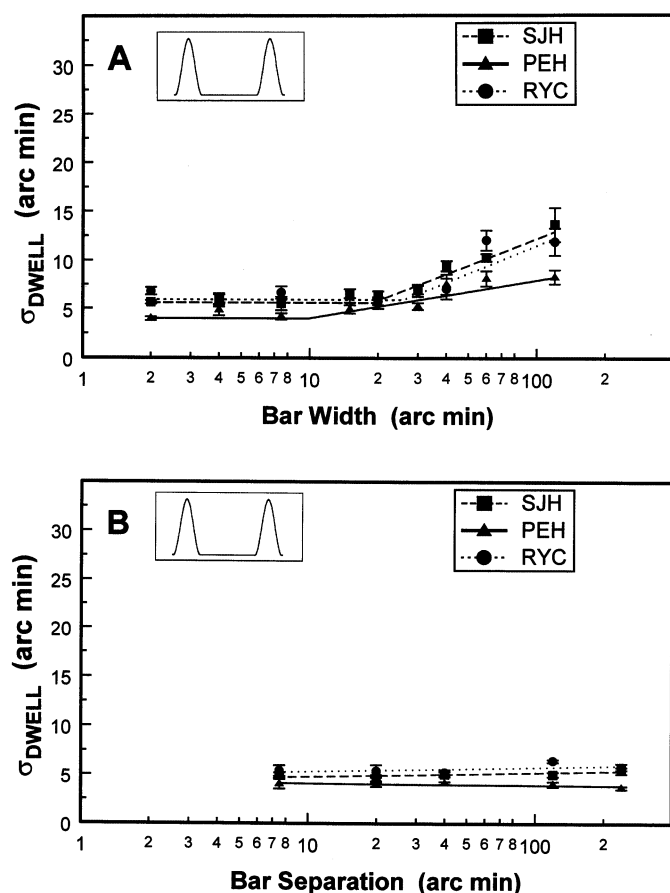


Fig. 6. Overall fixation variability versus (A) bar width in Exp. 3 (Separated Bars of Variable Width) and (B) bar separation in Exp. 4 (Separated Bars of Variable Spacing; bar width 2 min). Details as in Fig. 2. Note that the worsening in precision is associated with increases in bar width (A), not bar separation (B).

The landing points of crossing saccades are scattered and their variability shows no systematic dependence on bar width (heavy line, Fig. 8, left). Crossing-saccade bias is idiosyncratic and generally undershooting (Fig. 8, right, heavy line). The addition of > 15 min within-bar saccades substantially improves performance (shift to dashed line). The inclusion of all saccades > 7.5 min (dotted line) essentially achieves overall performance. The final or overall mean bias is near 0 min.

Fig. 9 shows a comparable, though partly contrasting, analysis for Exp. 4 data (i.e. Constant Width Bars of Variable Separation). Now the variability of crossing saccades increases with separation (Fig. 9, left, heavy line). Once again, addition of within-bar saccades of > 7.5 min (dotted line) essentially achieves overall performance (thin solid line). The bias of crossing-saccades to predictable bar targets shows no consistent pattern across all three subjects (Fig. 9, right).

Finally, there is considerable difference in the statistical distributions of crossing saccade landing points and the combined eye movement pattern. The former distribution is uniform across the region of the target bar

(flat or square wave distributions of starting and landing points, S.D. of starts much smaller than that of landings), while the dwell histogram based on the overall sequence of movements is strongly peaked (Figs. 1 and 5; leptokurtic distribution).

3.7. Is fixation a stationary process?

A possible concern in replicating our data is our choice of a standard 40-s trial duration. If fixation were non-stationary, as it may be in the absence of a visual target (Cornsweet, 1956; Matin, Pearce, Matin, & Kibler, 1966), this would be a problem because trial duration would matter. However, we repeated Exp. 3 (Variable Width Bars of Fixed Separation) but for 6-s trials, and found that overall σ_{DWELL} was equal to that found for the longer trials.

4. Discussion

4.1. Overview

The present study extends knowledge about target localization and the cooperation between the different types of eye movements. Dwell-time data depend to some extent on the observer and the display; however, all subjects and displays showed a dependence of overall variability on bar width, i.e. on target structure, not on bar separation. Filtering the records show that drift and saccades smaller than 7.5 min make no appreciable contribution to overall variability, measured as S.D. This was true for all subjects and bar widths, not only for Exp. 3 (Separated Bars, analyzed in Section 3.6) but equally for Exp. 2 (Adjacent Bars) and Exp. 5 (Single Bar), though those analyses have been omitted for brevity. Factors consistent with a constant approximately circular goal zone of 20 min width are (a) undershoot of bars in grating displays by about 10 min, (b) an optimal overall variability (S.D.) close to 5 min, (c) this last for bar widths smaller than 20 min (10–30 min), and (d) the repeatable finding that a threshold amplitude of about 7.5 min separates small movements that make little difference to variability from larger movements that do. Item (d) is consistent with previous impressions for other displays that small microsaccades make little or no contribution to performance (Steinman et al., 1973; Winterson & Collewyn, 1976; Kowler & Steinman, 1977; Bridgeman & Palca, 1980).

The present conclusions were reached by experiment and by analysis of dwell time histograms, but can be summarily illustrated (though less readily quantified) by plotting eye velocity against eye position as in Fig. 10 (Exp. 3, Separated Bars).

The concentration of fixations, i.e. low eye velocities, in the region of the bars is obvious. The large clockwise

loops are crossing-saccades with landing positions scattered across the region of the bar. The small hopping movements are within-bar saccades that carry the foveolar centre along to a narrowly defined take-off position. As expected from the goal-zone hypothesis, the full width of the take-off zone is about 20 min wide for subjects SJH and PEH. Much the same applies to RYC though the illustration is less clear.

Although we have presented a case for a constant 20-min goal zone we do not believe that this is forced anatomically by some ‘sweet spot’ of photoreceptor density within the foveola (e.g. Millodot, 1972), for a number of reasons: (A) *A homogeneous array of photoreceptors can behave as if there is a goal zone.* An ideal device with the optical characteristics of the eye and its photoreceptors (e.g. Campbell & Gubisch, 1966; Geisler, 1984) also shows evidence for asymptotic performance at bar widths less than 20 min; however, the variability of this simple ideal is < 0.1 min, which is about 40-fold better at all bar widths than is observed — so it is necessary to incorporate additional properties of the photoreceptors and visual cortex into the model (Sinha & Hallett, in preparation). (B) *A fixed goal zone does not explain between-trial variation.* If variability and bias are determined by a constant goal zone, twice the within-trial variance ($2 \times \sigma_{\text{DWELL}}^2$ /number of fixations) should be equal to the between-trial variance in the bias, because bias involves a difference of two independent means. There is some scatter across conditions and subjects but the fraction of the between-trial variance explained by within-trial variance is only

30%. The same conclusion was reached earlier in this laboratory, though the conditions, techniques and measures were different and the variances larger (work with Lightstone, 1973, cited in Hallett, 1986; non-contacting eye tracker, 8 min $\lambda = 507$ nm target spot at 100 times the dark-adapted foveolar threshold). (C) *There are cognitive factors.* Although the difficulty with between-trial variation can be met by postulating a larger (> 20 min) retinal goal zone, of which only one randomly chosen part is used in any fixation trial (Hallett, 1986), this effort to preserve a wholly low-level explanation may not offer much because it is known that fixation is generally more variable in a contrast discrimination task that does not specify precise fixation as part of the task instructions (Sinha, Hamstra, & Hallett, 1999). The present 20-min diameter goal zone may be better regarded as an estimate of the smallest possible task-dependent goal zone.

4.2. Previous work on target localization

4.2.1. End-primary saccadic error

End-primary saccadic error is subject to a psychological range effect (Kapoula & Robinson, 1986) but generally increases in mean undershoot and scatter with the retinal eccentricity of a *random* target displacement (e.g. Hallett, 1978). This overall picture, of error increasing with eccentricity, only partly agrees with our analysis of the end-errors of the crossing saccades to thin predictably positioned bars of variable separation (Exp. 4). Crossing-saccade variability does increase

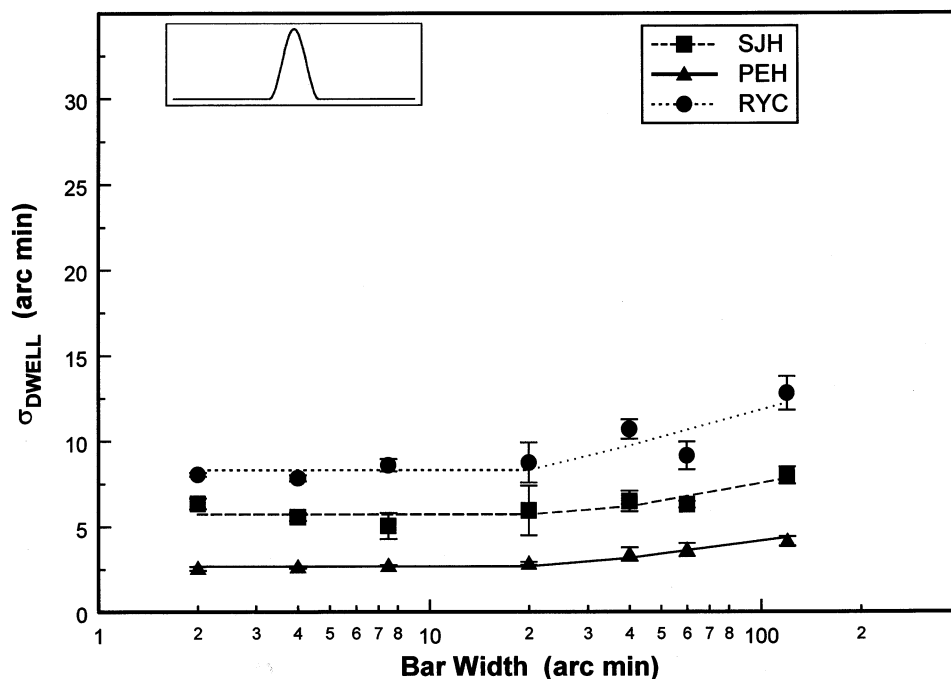


Fig. 7. Overall fixation variability for 40-s fixations of a single bar (Exp. 5). Single Gaussian fits were used to estimate σ_{DWELL} . Other details as in Fig. 2.

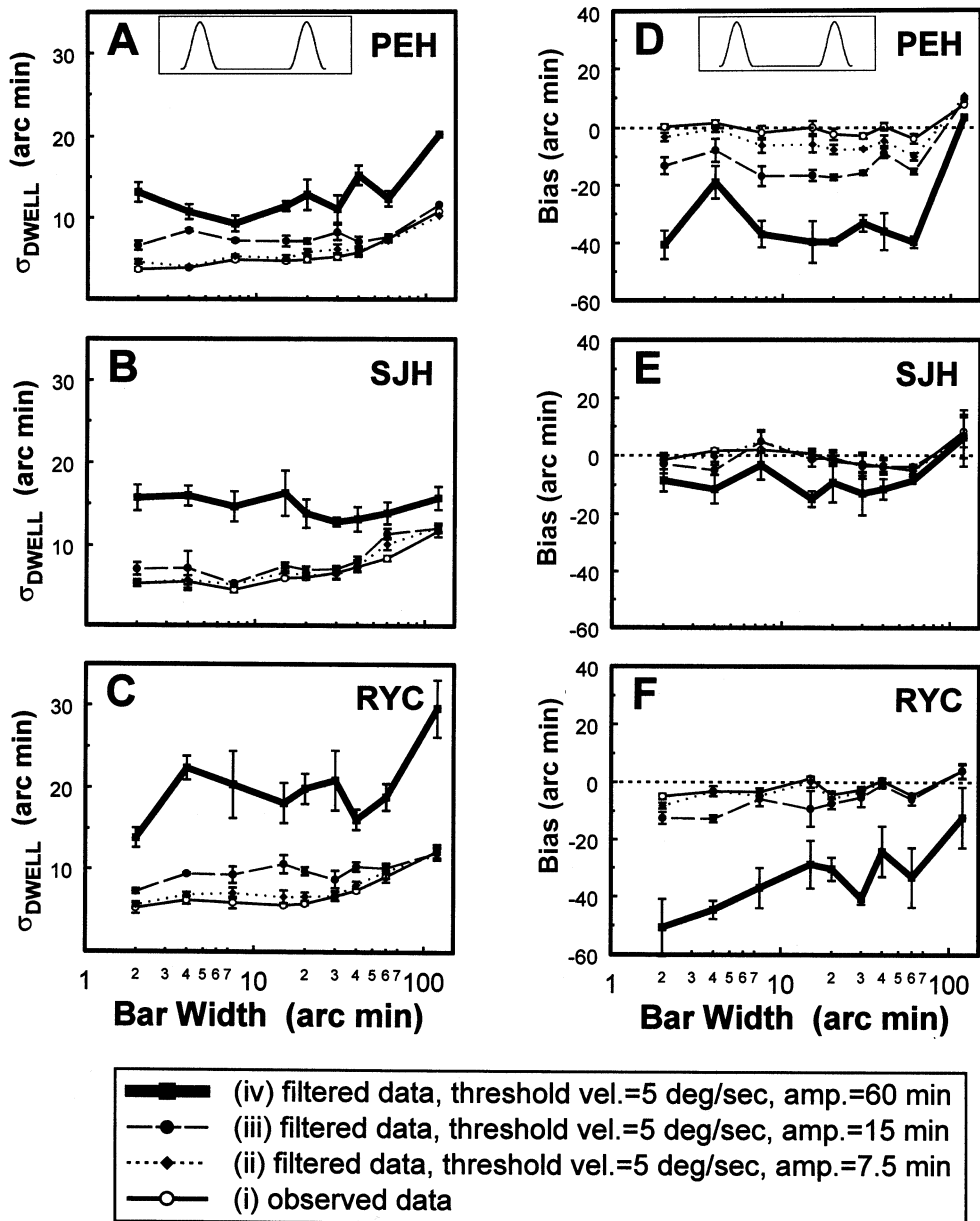


Fig. 8. Fixation variability (A–C) and under/overshooting bias (D–F) for the data of Exp. 3 (Separated Bars of Variable Width) for records filtered to remove different eye movements. (A–C) (i) Thin solid line is the unfiltered overall variability (i.e. data replotted from Fig. 6a), and (ii) dotted line shows almost the same values after the elimination of ocular drift and saccades < 7.5 min. (iii–iv) Dashed line and heavy line represent filtered data following elimination of increasingly larger saccades of amplitude 15 and 60 min, respectively. For example, dotted line (ii) shows that elimination of the smallest within-bar saccades of < 7.5 min affects variability only very slightly. Such small movements (the smaller microsaccades) do not improve precision. (D–F) Crossing saccades (heavy line) are generally undershooting, while overall performance, involving all eye movements, approaches zero bias. Each datum point on extreme right for subject PEH (A, D) represents a single observation.

with bar separation for subjects PEH and SJH (Fig. 9, left, heavy line), but end crossing-saccade error (under- or overshooting bias) for these predictable targets does not systematically increase with bar separation for all three subjects. Only subjects PEH and RYC show this tendency (Fig. 9, right, heavy line). The more useful comparison is not with the tracking of highly random targets, but between our crossing saccades and the high accuracy and precision of the primary saccades to displaced dot clusters which were only slightly random-

ized (5%) in position (Kowler & Blaser, 1995, two subjects). If allowance is made for the small numbers of subjects then our values for three subjects, though more variable, generally replicate theirs.

4.2.2. Fixational movements

Fixational movements are known to hold an already localized target precisely, a 25-min ring being one approximation to an optimal target (Murphy et al., 1975). This is consistent with variability being least for very

fine cosine bars of less than 20 min width in Exp. 1–3. The general agreement in σ_{DWELL} between Exp. 3 (Separated Bars) and classic studies of persistent fixation on a single target may be due to swift initial localization by crossing saccades, leaving about 36 s of a 40-s trial for ocular drift and within-bar saccades. Despite some 14–35 crossing saccades in a 40-s trial, with relatively widely dispersed landing points, it is primarily the medium and large within-bar saccades (7.5–30 min) that refine overall precision.

In summary, we have found that precision of repeated fixations to stationary separated targets depends on bar width for bars wider than 20 min, and not on bar separation. In addition, we have found that precision of

repeated fixations is primarily determined by large crossing saccades followed by smaller within-target saccades greater than 7.5 min amplitude. Drift and smaller saccades apparently play very little role in carrying out this task. These results are consistent with the existence of a functional goal zone of width 20 min. It remains unknown to what extent variations in task instructions would influence these separate oculomotor components. For example, it may be that crossing saccades greater than 7.5 min alone may be sufficient for a task involving comparison of fine detail. Continuing efforts are currently underway examining the implications of task instructions on oculomotor performance (e.g. Sinha et al., 1999; Hamstra, Sinha, & Hallett, 1999).

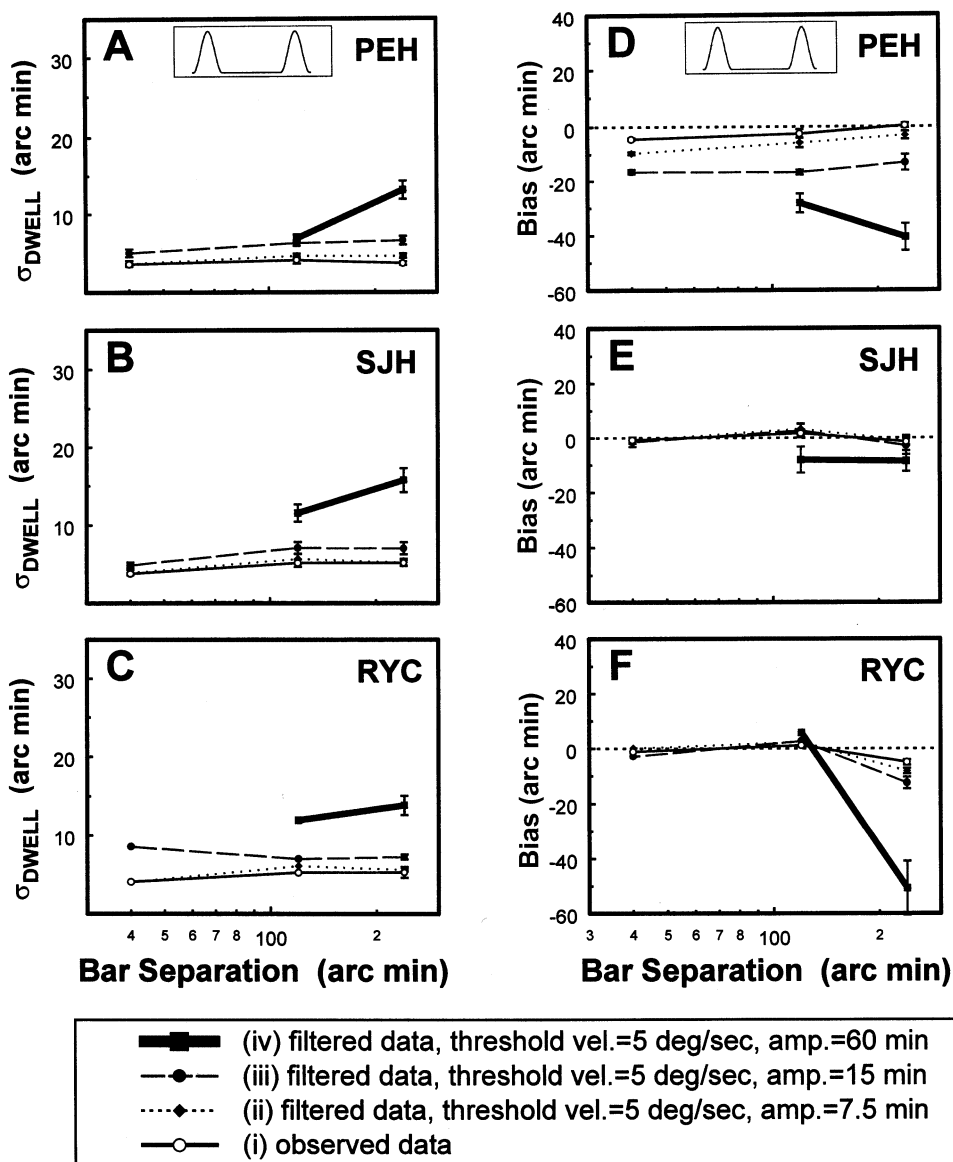


Fig. 9. Fixation variability and under/overshooting bias for the filtered data of Exp. 4 (Separated Bars of Variable Spacing) for all subjects. Other details as in Fig. 8. See text. Symbols with no error bars for subject RYC represent single observations.

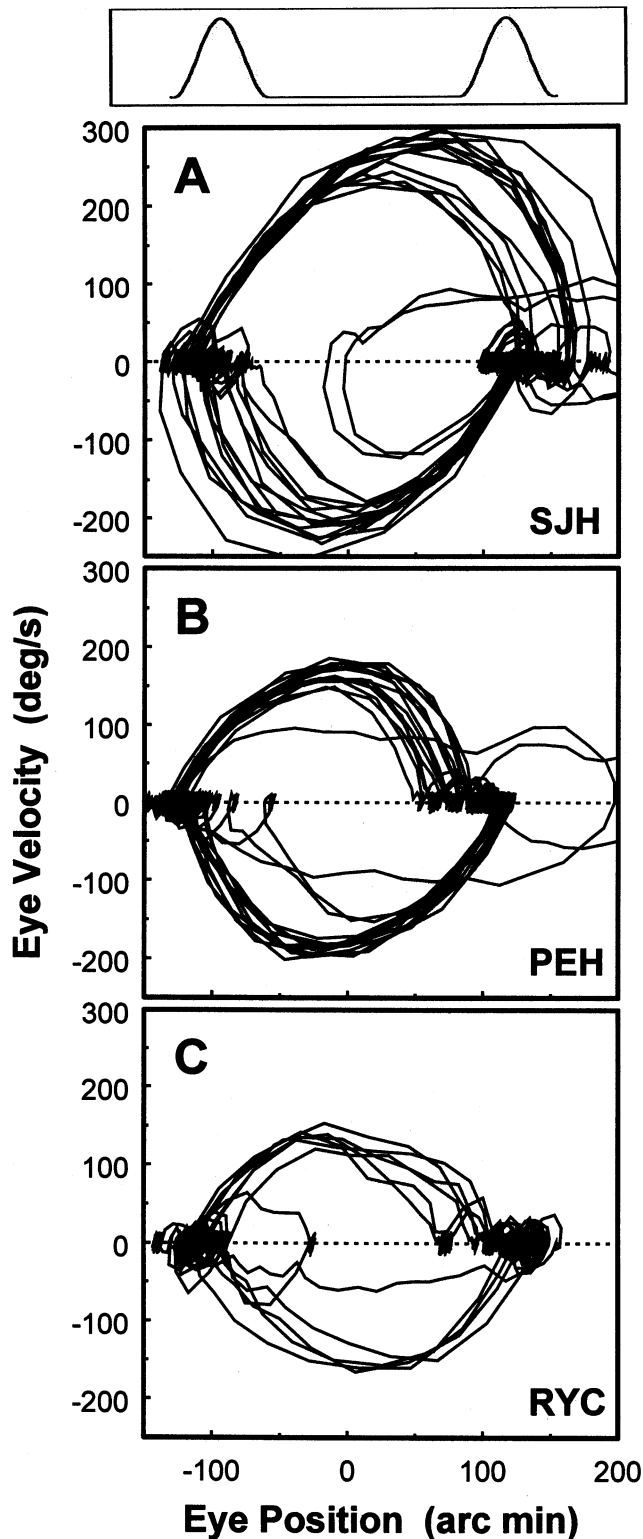


Fig. 10. State-space diagrams of Exp. 3 (Separated Bars of Variable Width) data for all subjects. Bar separation 240 min, bar width 15 min. This plot of eye velocity versus eye position shows the concentration of fixation positions (low velocities) over the two target bars. Assume clockwise direction to interpret plots. The crossing saccades have widely-staggered landing positions. The eye then hops (within-bar saccades) to a generally well-defined take-off locus whose width is consistent with a roughly 20-min wide retinal goal zone. A considerable magnification of the vertical scale would show the smallest microsaccades and ocular drift.

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