LATENCY/ACCURACY TRADE-OFFS DURING SEQUENCES OF SACCADES

by

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A thesis submitted to the

Graduate School-New Brunswick

Rutgers, The State University of New Jersey

in partial fulfillment of the requirements

for the degree of

Master of Science

Graduate Program in Psychology

Written under the direction of

Eileen Kowler

and approved by

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New Brunswick, New Jersey

January, 2010

ABSTRACT OF THE THESIS

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For many motor behaviors, the more time devoted to planning a movement, the higher the spatial accuracy. To determine whether trade-offs between planning time and accuracy apply to saccadic eye movements, the present study investigated whether Fitts's Law, which holds that movement time depends on traveled distance and the required level of precision, applies to sequences of saccades. Saccades were made in sequence to 4 stationary target circles. Target eccentricities and target sizes varied. The time to scan the targets increased with Fitts's Index of Difficulty (ID), (defined as $log_2 (2S / D)$, where S is target separation and D is target diameter), showing that Fitts's Law can apply to sequences of saccades. The increase was due mainly to a greater frequency of secondary saccades, rather than to increases in the latency of primary saccades. Analyses of saccadic accuracy showed that subjects used secondary saccades, rather than prolonging saccadic latency, to improve landing accuracy. Even where subjects were explicitly asked to increase saccadic latency (Experiment 2), the spatial distribution of landing positions of primary saccades did not change. These results showed that increasing the time available for saccadic planning did not improve the spatial precision of saccades. Saccades differ from some other motor behaviors, where optimal performance depends on trading off the duration of primary movements with the occurrence of corrections (Meyer et al., 1988). For saccades, the only apparently viable strategy to improve accuracy is to issue more corrections.

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1. General Introduction

The ability to trade-off speed and accuracy is a fundamental property of motor behavior. Traditional experimental situations for studying speed/accuracy trade-offs involve the measurements of movements, such as tapping, finger-pointing or wrist- rotations, that are directed to a certain location or to multiple locations. These procedures allow exploration of mechanisms that control many natural motor behaviors. This study deals with speed/accuracy trade-offs for sequences of saccadic eye movements.

Speed/accuracy trade-offs in motor performance have been described by Fitts's Law (Fitts, 1954). According to Fitts's Law, the time to complete a movement depends on both the movement distance and the required level of precision. Specifically, the average movement time (MT) will increase with the required precision of the movement and with the traveled distance:

$MT = A + B \log_2 (2S / D)$, where D represents the target diameter, and S represents the traveled distance. Fitts's Law has been investigated in numerous motor studies and has been found to hold for a variety of movements under different conditions (see Plamondon & Alimi, 1997, for a review). Although it has been applied to many kinds of motor tasks, Fitts's Law has not been accepted without controversy. The classic experiment involves highly spatially constrained movements, where subjects are instructed to move back and forth between two limited regions (Fitts, 1954). Some investigators suggested that different experimental conditions would produce different outcomes. For example, in a temporally-constrained condition, in which subjects produce movements of a specified duration, a linear function was found to fit better than the original logarithmic function (Wright & Meyer, 1983; Schmidt et al., 1979).

One interesting development in the study of Fitts's Law, and speed/accuracy relationships more generally, was due to Meyer et al. (1988). They proposed a "stochastic optimized-submovement model" to explain Fitts's Law in rapid aimed movements. They suggested that the aimed movements consisted of a primary submovement and an optional secondary submovement. They also assumed that the motor responses are affected by noise, which increases with movement velocity. A primary submovement with high velocity (short duration) would increase the likelihood of error (due to the greater noise), and thus require a time-consuming secondary submovement to correct the error. Secondary submovements could be avoided by slowing the velocity of primary submovements, but if too slow, this would also increase the total movement duration. Thus, the optimal strategy is to choose a duration that minimizes total movement time. The minimization of total movement time was, according to Meyer et al. (1988), a product of an "ideal compromise between the durations of primary and secondary submovements". This model made good predictions for rapid, spatially-constrained movements (Meyer et al. studied wrist rotations), and was consistent with Fitts's Law.

Although Fitts's Law has been studied for a variety of movements, its relevance to saccadic eye movements had not been well established. Studies have documented speed/accuracy trade-offs in saccadic eye movements, focusing only on the parameters of the saccade itself, such as saccadic velocity, amplitude and duration (Abrams et al., 1989; Harris & Wolpert, 1998). These studies showed that there is a linear trade-off relationship between saccadic velocity and the variability of endpoints. Saccadic planning time, the latency of the saccade, was not considered. Latency is typically ignored in studies of Fitts's Law. For saccadic eye movements, however, neglecting latency is not necessarily appropriate. Latency represents the time of sensory processing and decision-making and it seems reasonable that longer planning time could lead to better spatial precision (smaller variability of endpoints) or better saccadic accuracy (less average saccadic error, i.e., target undershoot or overshoot). Perceptual judgments of location improve (become more precise) with increasing processing time (Pizlo et al., 1995), and saccadic accuracy and precision improve with increasing latency in the case where targets are surrounded by distracters (Cohen et al., 2007; Coëffe & O'Regan, 1987; Ottes et al., 1985; Viviani & Swensson, 1982).

An influential treatment of saccadic latency with implications for latency/accuracy relationships was developed by Carpenter (1981). He proposed the LATER [Linear Approach to Threshold with Ergodic Rate] model of decision-making. In this model, there was a decision signal, S. This decision signal was assumed to increase linearly from an initial level, $S_{0,}$ to the threshold, $S_{T,}$ where the saccade is initiated. The rate of rise, r, varies randomly from trial to trial (Hanes & Schall, 1996). Due to this assumption, the reciprocal of saccadic reaction time (proportional to the rate of rise) is expected to be described by a Gaussian distribution. Carpenter and his colleagues showed that the LATER model could predict the distribution of saccadic reaction times under many circumstances (Hanes & Carpenter, 1999; Reddi & Carpenter, 2000). Saccadic accuracy, however, was considered only in terms of the probability of a movement in the correct direction in a two-choice task (Hanes & Carpenter, 1999; Asrress & Carpenter, 2001). Neither the spatial accuracy (average error), nor the scatter of saccadic endpoints, were considered.

Studies of saccades that did focus on spatial accuracy did not include systematic treatments of latency. Several studies of saccades made to track target step displacements found that saccades typically undershoot targets (particularly for large target displacements), with secondary saccades used to correct the residual error (e.g., Becker & Fuchs, 1969; Henson, 1978; Prablanc, Masse & Echallier, 1978; Abrams, Meyer & Kornblum, 1989). Kapoula (1985) and Kapoula & Robinson (1986), however, showed that saccades do not always undershoot. In their study, a target stepped to the right or left with unpredictable step sizes (range of sizes = 5 to 20 degrees). Saccades to the smaller target steps overshot the target and saccades to the larger target steps undershot (the "range effect"). Note that the range effect occurred when subjects tracked unpredictable target steps (target steps with randomly chosen direction – right or left) and sizes. When the target jumps were always 5 degrees to the right or the left, Kapoula and Robinson (1986) found no range effect and almost all saccades undershot the target. This implies that the range effect could be a consequence of uncertainty about target step size, i.e., saccades are influenced by the recent stimulus history (Falmagne et al., 1975; Kowler et al., 1984) and are biased toward the mean of the set of possible step sizes.

In agreement with a role for uncertainty, Kowler and Blaser (1995) did not find either systematic undershoots or a range effect in their experiments. They asked subjects to make saccades as accurately as possible to track random target displacements, even if this required longer saccadic latency. These instructions were intended to encourage saccadic planning to be based on the current stimulus, rather than on the past history of target displacements. Kowler and Blaser (1995) found no systematic undershoots, and no range effect. In addition, saccades were extremely precise (SD of landing positions was about 6% of target eccentricity) and precision was not impaired when the target size increased (target diameters from 1-4 degrees). Furthermore, the occurrence of secondary saccades decreased as the target became larger. These results suggested that, given enough planning time, the spatial performance of saccades can be extremely good. The high level of spatial performance in Kowler and Blaser's study may have been the result of a latency/accuracy trade-off, where taking more time led to more accurate saccades, in the same way that increased time can improve the precision of judgments of spatial location (e.g., Pizlo et al., 1995). But the results also may be attributed to strategies, where delaying saccades long enough after the target appears removed the effects of stimulus uncertainty. Specifically, with random target steps (high levels of uncertainty), people may tend to preprogram and make predictions even before the target appears, and these effects, which contribute to saccadic errors, are particularly evident when there is time pressure to respond quickly. One of the purposes of the present study is to address these competing explanations by investigating latency/accuracy relationships when uncertainty is minimized by having subjects make saccades to an array of stationary targets.

One recent study of saccadic latency with some implications for latency/accuracy relationships is Harwood et al. (2008), who discussed the issue in terms of spatial scale. Several prior studies had shown that latencies of saccades remain about the same across a large range of target displacement sizes (e.g., Frost & Poppel, 1976; Heywood & Churcher, 1980; but see Dick, Ostendorf, Kraft & Ploner, 2004), with latencies increasing when displacement size falls below about 1 deg (Kowler & Anton, 1987; Wyman & Steinman, 1973). Harwood et al. (2008), however, showed that saccadic latencies are modulated by the ratio of the target step size (0.5 to 12 deg) to target diameter (2, 4 or 8 deg). Saccadic latencies were longer for larger targets and small target steps (smaller step/diameter ratio) than for small targets and large target steps (large ratio). The effect of ratio was not observed in a comparable manual reaction time task in which subjects were instructed to respond with a button press. This implies that the ratio effect was limited to saccadic planning.

Interestingly, Harwood et al.'s result, where smaller target sizes would lead to larger step size/diameter ratios, and thus shorter saccadic latencies, is opposite to Fitts's Law, if we assume that Fitts's Law could be applied to latencies as well as movement times. According to Fitts's Law, higher required precision (smaller diameter) should require longer processing time for the motor response. In Harwood et al.'s experiments, subjects were instructed to make a saccade to the center of stimulus (a rotating segmented ring) when it moved to an unpredictable location. Thus, their result may have been influenced by uncertainty as well, rather than depending only on the spatial properties of target size and eccentricity (the ratio mentioned above). Other work showed that increasing target size did not affect saccadic accuracy or precision (Kowler & Blaser, 1995), at least when instructions to prolong latency were adopted. The diverse pattern of results suggests that the relations among saccadic latency, spatial accuracy and spatial scale, (which involves both target size and eccentricity), still need to be explored.

The goal of the present study is to create a more unified approach to understanding the relationship between saccadic latency, accuracy and precision, incorporating the roles of target size, eccentricity, as well as sequential planning. This work differs from previous studies of these topics in a number of ways:

First, saccades were made to targets in fixed, known locations. This method minimizes uncertainty about target timing and locations, which may affect strategies of saccadic planning.

Second, the present study uses multiple saccadic targets rather than a single target, to allow subjects to perform the sequence of responses, as motor tasks typically do. Making multiple saccades is more representative of natural visual tasks and can shed light on how the oculomotor system functions, in particular with respect to options and strategies of controlling speed and accuracy, in realistic situations. This means that observations focused on the pause time between successive saccades, rather than the latency of a single saccade performed in isolation.

Third, by examining performance of the saccadic sequences, this study considers multiple factors: the in-flight time of the saccades, the saccadic latency (i.e., the duration of the pauses between successive saccades), and any secondary saccades that might occur during intervals between successive saccades. The distinction between in-flight time and pause duration is a major difference between saccadic eye movements and many other motor behaviors. For example, in other motor behaviors, such as tapping or wrist rotations, sensory feedback can be perceived and processed during the movement. Thus, for these movements it could be assumed that there is no intermediate pause between the end of a primary submovement and the start of secondary submovement (Meyer et al., 1988; Saunders & Knill, 2005). For saccadic eye movements, however, the movement is so rapid that saccades cannot be reprogrammed once initiated, thus, the saccadic pause interval (latency) cannot be ignored. Investigating the effects of pause duration on the spatial properties of saccades may help us to better understand mechanisms of oculomotor planning.

Finally, Fitts's paradigm allows control of target size and target eccentricity within the same sequential task. Investigating the applicability of Fitts's Law to sequence of saccades provides a launching pad for understanding speed/accuracy and latency/accuracy trade-offs in saccadic planning.

2. Experiment 1: Methods

2.1. Stimulus display

Stimuli were displayed on a Dell P793 CRT monitor (13 deg × 12 deg; viewing distance 115 cm, 1.46 pixels/min arcs; refresh rate 75 Hz, non-interlaced).

There were 9 different types of stimuli which were defined by different target separations and target diameters. Each stimulus display contained 4 identical target circles which were arranged at the corner of an imaginary square. The separation was defined as the distance between the centers of two adjacent circles. The diameter of the circle was set to one of four values (15, 45, 90 or 180 min arc), and the separation was set to one of three values (64, 127 or 255 min arc). In order to avoid the superimposing of targets (large targets and small separations), only 9 combinations of size and separation were selected (see Table 1). The experimental condition on each trial was selected randomly from the 9 possible conditions.

2.2. *Procedure*

Before each trial, one of the target circles, randomly selected, was displayed on the screen (Fig. 1a, left). Subjects were instructed to fixate the circle and press a button to start the trial when ready. After the button press, the other three target circles appeared (Fig. 1a, right).

Subjects were instructed to choose their own direction of scan (either clockwise or counterclockwise). Directions were maintained throughout the experiment. They were instructed to begin from the initial fixation circle and to look at each circle in sequence at a brisk, yet comfortable pace. They were told to aim successive saccades at each target and not to miss or to skip any. The complete stimulus remained on for either 5 or 6 seconds depending on the subject. These durations were determined in a preliminary session to be sufficient to allow subjects to complete at least 2 loops around the four targets. Fig. 1b shows a sample eye trace, and Fig. 1c shows all of the target sizes and separations with a representative set of saccadic endpoints superimposed.

2.3. Subjects

Four subjects (LM, AW, JW and SLC) were tested, all with uncorrected vision, and all naïve to the experimental design and hypothesis.

2.4. Eye movement recording

Horizontal and vertical movements of the right eye were recorded using a Generation IV Double Purkinje Image Tracker (Crane & Steele, 1978). The left eye was covered and the head was stabilized with a dental biteboard. The tracker's voltage output was fed on-line through a low pass 100 Hz filter to a 12-bit analog to digital converter (ADC). The ADC, controlled by a PC, sampled the eye's position every 2 ms. The digitized voltages were stored for analysis. Tracker noise level was measured with an artificial eye after the tracker had been adjusted so as to have the same first and fourth image reflections as the average subject's eye. Filtering and sampling rate were the same as those used in the experiment. Noise level, expressed as a standard deviation of position samples, was 0.4′ for horizontal and 0.7′ for vertical positions. Recordings were made with the tracker's automatically movable optical stage (auto-stage) and focus servo disabled.

The beginning and ending positions of saccades were detected off-line by means of a computer algorithm employing an acceleration criterion (Gersch et al., 2004). Values of the criterion was determined empirically for individual observers by examining a large sample of analog recordings of eye positions. Saccades as small as the microsaccades that may be observed during maintained fixation (Steinman, Haddad, Skavenski, & Wyman, 1973) could reliably be detected by the algorithm.

2.5. Data Analysis

'Loop duration' was defined as the time spent completing a whole loop around the four targets. The first saccade in the loop was defined as the first initiated saccade after all targets appeared. The last saccade in the loop was defined as the final saccade returning back to the fixation circle, including any secondary saccades following the large primary saccade between successive targets. Results will be presented as 'time per segment', defined as the loop duration divided by the number (n) of targets, where n=4.

The primary saccade for each segment was defined as the first saccade which left from the target (N) to the next target (N+1). Primary saccades were often followed by a secondary saccade (see Fig. 1b). The time between consecutive primary saccades was termed the 'dwell time', which was the time spent looking near each target. Thus, dwell time includes any secondary saccades that may occur.

2.6. Numbers of trials tested and excluded

All subjects were tested 23-36 experimental sessions, where sessions contained 50 trials each, leading to a total of 1150 trials for LM, 1350 trials for AW, 1150 trials for JW and 1800 trials for SLC. About 4 to 5 sessions were tested each day.

In each trial subjects made 2 loops around the set of 4 targets. Loops could be discarded for a number of reasons: Loss of tracker lock (.3% for LM, JW and SLC; 2.2% for AW), latency of initial saccade < 100 ms (.3% for LM; 3% for AW; 7% for JW and 14% for SLC), or failure to complete the loop or stay on the path (i.e., skipped a target or changed direction) (3% for LM; 1.6% for AW; 9% for JW; 13% for SLC). The data reported were based on a total of 2226 loops for LM, 2516 for AW, 1928 for JW and 2602 for SLC. Some of the analyses to be reported were based on individual segments of a loop, where a segment is defined as the saccade or saccades made between successive targets. Each loop contained 4 segments.

3. Experiment 1: Results

3.1. Time to complete the saccadic sequence increased with the Index of Difficulty

Fitts's Law states that the time to complete a movement will increase with the Index of Difficulty (ID). Figure 2 plots the time per segment of a loop as a function of ID, where "time per segment" is defined as the time to complete the loop around the targets divided by 4, the number of targets in the loop. The results show that, in agreement with Fitts's Law, time/segment increased with ID. Results were similar for first and second loops (see Fig. A1 in the Appendix). There were differences among the subjects in the magnitude of the effects, with subject LM showing a very shallow slope. The analyses below were done to determine what was responsible for the Fitts's Law behavior by examining the different components of performance (saccade duration; inter-saccadic dwell times) as a function of ID, and also as a function of target size and separation.

3.1.1. Time per segment as a function of target size and separation

In traditional treatments of Fitts's Law, the effect of increasing target separation on movement time can be compensated for by increasing target size: increasing separation leads to slower movements;

increasing size leads to faster movements. Figure 3 shows that such a trade-off between effects of separation and size did not always apply to saccades. For JW, who showed the largest effect of ID (Fig. 2), both target size and separation influenced performance – time/segment increased with separation and decreased with size (Fig. 3). The pattern was similar for AW, however, the effects were smaller. For the other two subjects, LM and SLC, time/segment increased for smaller targets, but did not increase for larger target separations. The effects of size and separation will be explored further in the next set of analyses.

3.1.2. Saccadic duration and dwell time examined separately

The effects of target size and separation (Fig. 3) might be understood by examining two different components of performance separately: The duration of the large primary saccade that took the line of sight from one target to the next, and the "dwell time", the time spent looking at or near each target between consecutive primary saccades. Note that with this definition, dwell time will include any secondary saccades that may have occurred between consecutive primary saccades.

Saccadic duration. Figure 4 shows that the duration of the primary saccade increased with target separation and was not affected by target size. The effect of separation is consistent with classical findings of increases in saccadic duration with saccadic amplitude (Becker, 1989).

Dwell time. Figure 5 shows dwell time for the different sizes and separations. Dwell time increased as target size decreased for all subjects. The magnitude of the effects of target size varied among the subjects, ranging from about 10-20 ms for LM and AW, to 80 ms for JW. Dwell time decreased with target separation for all subjects, except JW. (Fig. A2 shows dwell time as a function of the ordinal position of the target in the sequence.)

3.1.3. Summary

The time to complete a sequence of saccades increased with Fitts's Index of Difficulty. These effects can be attributed to the increasing dwell time as target size decreased (Fig. 5) and to increasing saccade duration with increasing target separation (Fig. 4). Note that although the larger target separations increased the duration of the saccades, these effects were offset to some extent by the decreases in dwell time with separation (Fig. 5).

The next sections examine the dwell time in more detail, focusing in particular on the role played by secondary saccades.

3.2. Dwell time

3.2.1. Contribution of secondary saccades

Meyer et al. (1988) reported that secondary submovements were important in the performance of manual tasks. They found that secondary submovements occurred more frequently as ID increased, and proposed that performance was the product of a trade-off between the occurrence of secondary submovements and the time spent on the primary submovements. To evaluate this proposal for saccades, secondary saccades were analyzed.

The frequency of secondary saccades was computed as the number of primary saccades followed by secondary saccades divided by total number of primary saccades. (Dwells with more than one secondary saccade were rare, less than 2 % for JW and less than 0.05% for the other subjects.) Figure 6 shows that secondary saccades became more frequent with increasing ID, with frequency increasing as either target separation increased, or as target size decreased. Except for LM (who rarely made secondary saccades), secondary saccades occurred in at least half the dwells for the most difficult case (largest separation; smallest size), and in about 10% of the dwells for the easiest case (smallest separation; largest size). The majority (about 75%, across subjects and conditions) of the secondary saccades were corrective, meaning that they brought the line of sight closer to target center. Secondary saccades corrected for either under- or overshoots of primary saccades (to be discussed below).

Secondary saccades prolonged dwell times. Figure 7 shows that dwell times with secondary saccades were about 50-75 ms longer than dwells without secondary saccades. (The dwell times shown in the figure did not include the in-flight time of the secondary saccades.) This amount is about one-third to one-half of the typical saccadic latency (where typical latencies are ~150 – 300ms). Note that when dwells with or without secondary saccades were examined separately, both decreased with separation (JW, who showed little effect of separation, is the exception) and neither showed consistent effects of target size (Fig. 7).

This analysis shows that inclusion of more dwells with secondary saccades accounted for the increases in average dwell times with smaller targets (Fig. 5). Larger separations also produced more secondary saccades (Fig. 6), but this did not result in an overall increase in dwell time (Fig. 5) except for JW. For the remaining 3 subjects, the effect of adding secondary saccades for large separations was offset by the decrease in dwell time with increasing separation. This can be seen in Fig. 7, and also in supplementary Tables A1-A3, where dwell times with and without secondary saccades are shown for all target sizes and separations.

The longer duration of dwells containing secondary saccades rules out strictly parallel and independent planning of primary and secondary saccades. If the planning of secondary and primary saccades had been parallel and independent, there would have been no effect of the secondary saccades on dwell time. The pattern of results also rules out strictly serial planning of primary and secondary saccades. This is because the observed increase in dwell time (50-75 ms) due to the secondary saccades was far less than the typical saccadic latency (>150 ms). This small increase rules out strict serial planning, where the preparation of each saccade can occur only after the current saccade is completed. The results are consistent with findings of overlap in the planning of multiple, successive saccades (McPeek et al., 2000; McPeek and Keller, 2002).

3.2.2. Were secondary saccades due to hurried planning of primary saccades?

The previous section showed that secondary saccades became more frequent with increasing ID (i.e., larger separations; smaller targets). Were secondary saccades needed because subjects rushed, and made short-latency primary saccades that were inaccurate, and thus needed a secondary saccade in order to achieve better accuracy? Such a trade-off between the time devoted to the primary movement and the occurrence of a secondary movement would be consistent with the findings of Meyer et al. (1988) for manual responses.

If short-latency primary saccades led to a higher proportion of secondary saccades, then the latencies of primary saccades that were followed by secondary saccades should be shorter than the latencies of primary saccades that were followed by another primary saccade.

To test the hypothesis, primary saccades were divided into four groups, depending on both the prior and the subsequent saccades:

Primary saccades (P) that were preceded by a secondary saccade (s) and:

a. followed by another primary saccade (p) (sPp)

b. followed by the secondary saccade (s) (sPs)

Primary saccades (P) that were preceded by a primary saccade (p) and:

c. followed by another primary saccade (p) (pPp)

d. followed by the secondary saccade (s) (pPs)

For example, the notation "sPp" means that the saccade prior to the primary saccade was a secondary saccade; the saccade after the primary saccade was another primary saccade.

Figure 8 shows that secondary saccades were not caused by a decrease in the latency of primary saccades. In fact, the latency of primary saccades followed by a secondary saccade was slightly greater than the latency of primary saccades followed by another primary saccade (sPs vs. sPp, and pPs vs. pPp). The latency of primary saccades depended mainly on the prior saccade. If the prior saccade was a secondary saccade (sPp and sPs), the current primary saccade had a shorter latency. These results suggest that secondary saccades did not occur due to inadequate time devoted to planning primary saccades. Instead, the occurrence of secondary saccades was more likely to be due to limitations in the spatial accuracy and precision of the primary saccades.

In support of the importance of the spatial factors in predicting the occurrence of secondary saccades, Figure 9 shows that the average spatial offset of the primary saccadic endpoints from target center was larger for primary saccades followed by secondary saccades (pPs, sPs) than for primaries followed by another primary (sPp, pPp).

3.3. Saccadic accuracy and precision

The analyses below focus on the spatial accuracy and precision of primary saccades across the different target sizes and separations, and the relationship between the saccadic accuracy and precision and dwell time.

3.3.1. Undershoot or overshoot?

It is often assumed, on the basis of studies of saccades made in response to unpredictable target jumps, that saccades undershoot targets, requiring secondary saccades to correct for residual error (see Introduction).

In order to determine whether undershooting accounted for the frequent occurrence of secondary saccades, the next analysis examined offset of the saccadic endpoint of primary saccades relative to target center along the principal meridian of the saccade. The ‘principal meridian’ was horizontal for targets separated horizontally, or vertical for targets separated vertically. When primary saccades undershot, the magnitude of offset from the center was signed negative; otherwise, the offset was signed positive. Figure 10 shows that average signed offsets were small, 10’ or less, even for the largest (250’) separation. Overshoots were about as common as undershoots, although there was a tendency for more undershooting when the targets were smaller. Secondary saccades occurred with about the same frequency for undershooting and overshooting errors.

3.3.2. Scatter of landing positions

The results in Fig. 10 show no consistent relationship between average signed saccadic offset from center and either target size or separation. The same was not true, however, for the scatter of landing positions.

Scatter was analyzed by computing the two dimensional scatter of landing positions (Steinman, 1965; Vishwanath & Kowler, 2004). Two dimensional scatter was quantified by the bivariate contour ellipse area (BCEA):

{Bivariate area $A = 2\pi k * \sigma_H * \sigma_V * (1-\rho^2)^{1/2}$}

where the σ_H is the standard deviation of the horizontal offset error (where ‘offset error’ is the distance between the saccadic endpoint relative to the center of the target); σ_V is the standard deviation of the vertical offset error, and ρ is the correlation coefficient of the horizontal and vertical offset errors. The value of k was set to be 1.125, which corresponds to BCEA containing 68 % of the landing positions.

Saccades were divided into two groups: initial saccades and final saccades. The ‘initial’ saccade was the primary saccade leaving from target (n) and heading to target (n+1); the ‘final’ saccade was the last saccade that landed at target (n+1). Thus, if there were secondary saccades, the final saccade would be the last secondary saccade. On the other hand, if there were no secondary saccades, the final saccade would be the same as the initial saccade. (Instances of more than one secondary saccade in a dwell were rare, see section 3.2.1.) Figure 11 shows that the scatter was, as expected, smaller for final saccades than for initial saccades, and smaller for smaller targets. The scatter of both the initial and the final saccades increased with increasing target separation. Similar results were obtained by plotting the average magnitude of the saccadic offset from the center rather than the BCEA (Fig. A3), and when analyses were restricted to the cases where the "final" saccade was always a secondary saccade (Fig. A4).

This analysis shows that secondary saccades were useful in reducing the scatter of landing positions. However, secondary saccades became less effective as target separation increased, as shown by the increase in final scatter with increasing separation. This result suggests that there was an adjustment in criterion as to what constituted an acceptable landing location, with the region of acceptability scaling up with target separation. This scaling may represent a sacrifice of some level of accuracy to avoid further prolonging of the scanning time with additional corrective saccades.

3.3.3. Relationship between landing error and dwell time

One motivation for this study was to determine whether increased saccadic planning time leads to improved saccadic precision, analogous to the improvements in movement precision associated with slower movement speeds in manual tasks (e.g., Meyer et al., 1988). Analyses described above (Fig. 8) showed that increased latency was not associated with a diminished need for secondary (corrective) saccades. To further examine the relation between planning time and saccadic landing position, the correlation between the dwell time preceding each primary saccade and the offset error of the primary saccade was computed for each condition.

Figure 12 shows a representative scatter plot of dwell time *prior to* each primary saccade vs. the offset error of the primary saccade. Data are shown for subject JW for the smallest target and largest separation. The correlation (r) between dwell time prior to the saccade and the offset error is .01. Correlations for all other sizes, separations and subjects showed similar patterns, with correlations ranging from -0.08 to 0.14. These results show that longer dwell times – longer time devoted to saccadic planning –

did not improve the accuracy of the primary saccade. (See Table A4 in the Appendix for confirmation with a slightly different analysis that took time devoted to planning secondary saccades into account.)

To summarize the relationship between dwell time and saccadic precision over all conditions, Figure 13 shows average dwell times (from Fig. 5) vs. the scatter of the final landing positions (bivariate area of final saccades, from Fig. 11) for all conditions. Conditions with longer average dwell times corresponded to those that were associated with conditions that produced a smaller scatter of endpoints. For variations in target size this relationship was expected, given the increased frequency of longer dwells due to the secondary saccades with the smaller targets (Fig. 6). For variations in target separation, multiple factors were involved in accounting for the shorter dwell time and larger scatter for the larger separation. These factors included the overall decrease in dwell time with increasing separation (Fig. 7), as well as the increased scatter of final landing positions as target separation increased (Fig. 11).

3.3.4. Offset error preceding secondary saccades

The results so far revealed a strong role for secondary saccades, in contrast to increased planning time, in improving the accuracy of the landing position. How far did the line of sight have to land from the target before a secondary saccade became likely? Harwood et al. (2008) reported that the probability of making a saccade to track a target step displacement depended on the ratio of target step size to target diameter, with smaller ratios leading to fewer saccades and longer saccadic latencies. The secondary saccades in the present experiment occurred under conditions similar to many of the primary saccades studied by Harwood et al. because in both situations the line of sight was relatively near the center of the target before the saccade occurred.

We found that the secondary saccades in our experiment had similar properties to the saccades Harwood et al. investigated, specifically, the occurrence and the latency of secondary saccades could be predicted by the ratio of error to target radius. In our case, ‘error’ refers, not to the size of a target displacement, but to the average offset error left behind by the primary saccade, where ‘offset error’ is defined as the distance of the line of sight to target center. Figure 14 shows that secondary saccades were infrequent (<10%) for ratios of <=1, i.e, cases where the line of sight landed within the target’s boundary, regardless of the target separation. The occurrence of secondary saccades increased as the ratio of error to target radius increased. In addition, the latency of secondary saccades generally decreased as the error/size ratio increased (Fig. 15). (Fig. A5 in the Appendix shows latency of secondary saccades as a function of target size and separation.)

These results above are similar to those of Harwood et al. (2008). One interesting difference was that we found that once ratios of offset error to radius exceeded 1, the probability of making a secondary saccade also depended on the initial target separation, with larger initial separations leading to an increased proportion of secondary saccades (Fig. 14). These effects of separation show that "global" or contextual effect (initial target separation) contributed to performance, and not just the immediate retinal conditions.

3.4. Summary

Fitts's Law applied to sequences of saccades. The effect was due mainly to the longer dwell times associated with the occurrence of secondary saccades for smaller targets, and to the increases in saccadic duration with larger target separations. There was no evidence that slowing the pace of scanning (increasing saccadic latencies) improved the spatial precision of saccades, a result that agrees with recent findings that the saccadic gap effect could not be explained by speed-accuracy trade-offs (Jin and Reeves, 2009). Secondary saccades, not increased planning time, were the principal means of reducing landing error. The results also showed a clear aversion to increasing the time spent dwelling on each target. When the target separation increased, subjects preferred to tolerate error – with the saccade landing further from the target – rather than prolong dwell time by making additional corrective saccades.

These results are different from the results of Meyer et al (1988). For their manual task, the spatial precision of the movement could be improved either by improving the accuracy of the primary movement (increasing its duration) or by making additional secondary submovements. For sequence of saccades, however, unlike manual responses, there were fewer options. There was no evidence that increasing the time devoted to the primary movement (that is, prolonging the latency portion) would reduce the scatter of landing positions). Additional analyses confirmed that the velocity of the primary saccade itself was not correlated with the size of the landing position offset error (see Table A5 in the appendix). Instead, secondary saccades were used to correct landing errors. The longer latencies of primary saccades not only failed to reduce the probability of occurrence of secondary saccades (Fig. 8), but were also not helpful for improving saccadic accuracy (Fig. 12).

Perhaps this pattern of performance occurred because the range of observed dwell times was too small. In order to evaluate this possibility, a second experiment was run in which a larger range of dwell times were encouraged by instructing subject to adopt different paces of scanning

4. Experiment 2: Methods

The goals of Experiment 2 were: (1) to test whether Fitts's Law would apply to sequences of saccades when different time constraints were applied, and (2) to investigate whether prolonging saccadic planning time by mean of instructions would improve saccadic precision. This will show whether the finding in Experiment 1 of no effects of increased planning time on precision was due to a strategy of not waiting long enough before launching the saccade. As a preview, the pattern of results of Experiment 2 was quite similar to that of Experiment 1 in that overall scanning time, as well as the proportion of secondary saccades, increased with ID. Subjects did slow the rate of scanning, but the additional time did not improve saccadic accuracy.

4.1. Subjects

Three new subjects were tested (DW, JS and EN). All had normal vision and no correction, and were naïve as to the experimental design and hypothesis.

4.2. Stimulus display and procedure

The stimuli were displayed on Viewsonic G90fb monitor. Movements of the right eye were recorded by an Eyelink 1000 (SR Research) tracker (tower mount) with head held by a chin and head rest. Viewing was monocular.

Stimuli were much the same as in Experiment 1. The diameter of the target circles were set to one of four values (15, 45, 90 or 180 min arc), and the separation was to one of four values (64, 128, 256 or 512 min arc). For the comparability of Index of Difficulty across experiments, purpose, not all combinations of size and separation were tested. A total of 10 conditions were tested, as listed in Table 2. The sequences of frames during trials were the same as Experiment 1. Trial length was 6 seconds.

4.3. Instructions

Two types of sessions were run, denoted "fast" and "slow". For the initial experimental sessions, subjects were instructed to make sequences of saccades at a comfortable and natural speed (same instruction as in Experiment 1). If they made saccades at rapid pace (defined as 3 or more loops around the 4 targets/trial), these sessions would be defined as the "fast" conditions (subjects DW and JS). In subsequent sessions subjects DW and JS were asked to scan at a slower pace (about 2-3 loops/trial). Subject EN initially made about 2.5 loops/trial. This was defined as his "slow" pace, and in subsequent sessions he was asked to speed up (3.5-4 loops/trial). Fast and slow sessions were tested alternately.

4.4. Experimental sessions

Each experimental session contained 40 trials and subjects were tested in 4-5 sessions/day. The experimental condition (target size and separation) on each trial was selected randomly from the 10 possible conditions (see Table 2).

5. Experiment 2: Results

5.1. Time per segment and secondary saccades

Time/segment increased with ID for both fast and slow conditions for DW and JS. For EN, time/segment did not vary much with ID (see Fig. 16). Time/segment in the slow condition was about 50% longer than in the fast condition. The average time/segment in the "fast" condition was comparable to that found in Experiment 1 (Fig. A6 in the Appendix shows the results broken down by separation and diameter; patterns are very similar to Experiment 1). These results provide additional evidence that Fitts's Law applies to sequences of saccades, despite the changes in the overall pace of scanning.

5.2. The occurrence of secondary saccades

As in Experiment 1, secondary saccades became more frequent as either target separation increased, or as target size decreased (Fig. 17). There were more secondary saccades in the slow condition than in the fast condition, and many dwells in the slow condition contained more than one secondary saccade. (See Figs. A6 and A7 in the Appendix for dwell times, which followed the same patterns as in Experiment 1.)

5.3. Did saccadic precision improve?

In order to investigate that whether prolonging the scanning time improved saccadic precision, the scatter of landing positions in the fast and slow conditions were analyzed. Figure 18 shows the initial (top) and final (bottom) scatter, with performance in the fast condition plotted against performance in the slow condition. For initial saccades, most of data points fell near the diagonal, showing that despite the large difference in dwell times across the fast and slow conditions (dwells were 260-380 ms under the fast condition; 460-560 ms under the slow condition; see Fig. A7), there was no reduction in the scatter of initial saccadic landing positions. Scatter of final saccades was improved in the slow condition for DW and EN, for the largest separation, reflecting the contribution of the additional secondary saccades. These results show that providing additional time to plan saccades had virtually no benefit for the precision of the primary saccadic movements, and little effect, beyond allowing time for more corrections, on the final movements.

5.4. Summary:

Experiment 2 demonstrated that Fitts's Law held for sequences of saccades with two additional subjects (DW and JS) and two different rates of scanning. For the third subject (EN), scanning rates were about the same for the different values of ID.

The results also showed that large differences in saccadic planning time did not affect saccadic precision. The failure to find a relationship between saccadic planning time and precision in Experiment 1 was not due to the absence of long dwell times. Even when dwell times were prolonged, as was the case in Experiment 2, the extra time was not used to reduce landing errors. Subjects allowed substantial error to remain in their landing locations and did not elect to use the available time to reduce the offset error.

6. General Discussion

6.1. Speed/accuracy trade-offs

Fitts's Law represents a trade-off: longer movement distances, or greater required precision, require more movement time. The present study showed that, in agreement with Fitts's Law, trade-offs between time and precision apply to sequences of saccades: sequences with smaller targets, and in some cases, larger target separations, took more time to complete.

In general, improving precision at the expense of movement time can be achieved by applying a variety of different strategies. For example: (1) slowing movement speed; (2) taking more time to plan the movement (longer latency); or (3) making additional secondary submovements, would all lead to improved spatial precision at the expense of time. Studies of Fitts's Law as applied to motor behaviors (other than saccades) showed effects of the first and third strategy above, namely, slowing movement speed and making additional submovements were both effective in improving the spatial precision of the movements. For sequences of saccades, the third strategy listed above, making secondary submovements, was the preferred way of sacrificing time in order to achieve the required level of precision.

These results can be compared to a prior study of Fitts's Law by Meyer et al. (1988). They found that for manual responses – rapid wrist rotations – the occurrence of secondary submovements resulted from a trade-off with the duration of primary submovements. Secondary submovements became more frequent when the primary submovement was too fast, and thus more likely to land outside the target region. The optimal strategy required finding the appropriate compromise between the durations of primary submovements and the frequency of secondary submovements. For saccades, on the other hand, such compromises were not applicable. Adjusting the speed or duration of the primary movement is not a viable option because the speed and duration of a saccade are determined by its amplitude. (Amplitude is the primary determining factor when the head is fixed. When saccades are made while the head is free to move, changing task constraints can lead to changes in saccadic duration independent of amplitude, see Epelboim et al., 1997). The present results showed that adjusting the latency (planning time) of primary saccadic movements in order to improve accuracy was not a preferred strategy. Instead, accuracy was improved by making secondary saccades to correct landing offset error of primary saccades.

Note that traditional Fitts's results account for the movement time, not latency. The latency, which may represent the time for visual information processing before executing any movement, was found to be independent of target parameters (target separation and target width) (Fitts & Peterson, 1964). Klapps (1975), however, found that latency increased as target diameter decreased, but only for short amplitude movements. This result implies that programming of short movements could occur prior to movement initiation (during the latency period), but for long movements, the programming is modified during the movement itself. By contrast, programming of saccades, similar perhaps to the short motor movements described by Klapps (1975), rely on programming done during the latency interval before the movement execution.

As noted above, secondary saccades, which took time to plan and execute, were the principal means of improving landing precision. The occurrence of secondary saccades was not due to insufficient time devoted to planning primary saccades. It is possible that taking more time to plan saccades could have improved accuracy, had such effort been made. We did not ask subjects to deliberately try to improve accuracy, but simply to look at each target. The results showed that in no case – a total of 6 subjects across the two experiments, including conditions in Experiment 2 where enough time was available – was there evidence for a preference to improve accuracy or precision by increasing saccadic planning time. The preferred option was to improve the accuracy and precision of landing by means of secondary saccades.

6.2. What triggered the secondary saccades?

Given the prominent role played by secondary saccades in controlling saccadic landing accuracy, it is important to look for the factors that triggered the secondary saccades. The higher proportion of secondary saccades in some conditions (small targets, large eccentricities) could have been due to insufficient time devoted to planning the primary saccades. Analyses showed, however, that the latency of primary saccades was slightly longer for primary saccades that were followed by secondary saccades than for primary saccades that were followed by other primary saccades (section 3.2.2). This suggests that secondary saccades were not caused by inadequate time devoted to the planning of primary saccades. Instead, secondary saccades appear to reflect the inherent limitations of the spatial precision of saccades.

The occurrence of secondary saccades was also not triggered by systematic undershoots of primary saccades. We did not find systematic undershoots. It has often been reported that saccades undershoot targets by about 10% and require secondary saccades to correct the residual error (Becker, 1991). The absence of undershoots in our experiment may have been due to the use of stationary targets, which reduce uncertainty about target timing and locations, or due to the use of multiple targets, which allowed subjects make sequences of saccades. Our result agrees with prior studies showing no systematic undershoot with saccadic sequences (e.g, Lemij & Collewijn, 1989, who used periodic target steps).

The secondary saccades we found were useful because the spatial variability of the landing positions of primary saccades was large enough, in some conditions, to lead to unacceptably large landing errors (either under- or overshoot). How large did the landing error have to be before a secondary saccade became likely? We addressed this question using an analysis proposed by Harwood et al. (2008). They did not study secondary saccades, but instead showed that the probability of making a primary saccade, and the latency of primary saccades, in a step-tracking task, depended on the ratio of target step size to the target diameter. A smaller ratio (large target and small step) led to longer saccadic latencies and reduced the probability of making a saccade to track the step. We found that secondary saccades showed similar patterns to what Harwood et al. reported, namely, a smaller ratio of eccentricity/radius led to longer latencies of secondary saccades and to a lower probability of making secondary saccades (section 3.3.4).

Secondary saccades were rare when the ratio of eccentricity to radius was smaller than 1, that is, when the line of sight was already within the target. These results are comparable to Harwood et al.'s (2008), but overall, the probabilities of making a saccade (primary saccades) in their experiment were higher than the probability of making a secondary saccade in the present study. This difference may be due to the fact that in Harwood et al. subjects were asked to track the unpredictable target steps, while in the present study secondary saccades were an option.

Our result was similar to what would be expected from Meyer et al.'s (1988) model, in that secondary submovements would be used to reduce the error when the primary submovements lands outside the target. The difference between ours results and theirs, however, is that the occurrence of secondary saccades was not the consequence of a trade-off with the duration (or latency) of primary saccades. Rather, given that smaller saccades have less variability in landing position than larger saccades (Abrams et al., 1989; Wyman & Steinman, 1973; also Fig. 11), making a sequence of two saccades (primary and secondary) may have led to less variability of the final landing position than a strategy of attempting to plan a single and large primary saccade. This strategy of relying on secondary saccades to clean up error would be the only feasible option if either (a) the variability of the primary saccades was limited by spatial factors and could not be reduced by more planning time or more deliberate efforts, or (b) the time or effort involved in improving the accuracy of any given primary saccade would have been too great to warrant use of such a strategy. Although both options could explain the results, our results favor the first possibility because we found that even when ample time was provided (Experiment 2) the precision of primary saccades did not improve.

Interestingly, we also found that the probability of making secondary saccades relied not only on the ratio of retinal eccentricity/target radius, but also on the target separation. That is, given the same retinal error following the primary saccade, the larger the previous primary saccades, the more likely secondary saccades would occur. This implies that even before a given primary saccades was executed, the saccade system already took target separation (or, expected primary saccade size) into account and started to evaluate the need for a secondary saccade. Perhaps this is because larger saccade size is expected to have larger landing variability (Harris & Wolpert, 1998). Thus, even when the primary saccades in the difficult condition (larger target separation) landed at with the same retinal error as in an easier condition (short target separation), secondary saccades, which were expected to have a higher probability to be needed in this condition, were more likely to occur. This suggests that planning secondary saccades took into account both local factors (retinal error) and global factors (target separation). This is unlike what Meyer et al. (1988) proposed, where secondary submovements passively depended only on the local error caused by primary submovement. Taking the visual information from both global and local factor may guarantee the efficient use of secondary saccades. The global information (target separation) acts as a “prior” so that the need for a secondary saccade can be predicted. This strategy allows the saccadic system started to evaluate the need for secondary saccades even before the landing error signal from primary saccades is received.

6.3. Latency/Accuracy trade-offs in sequences of saccades

As argued above, increasing the time available to plan primary saccades did not improve saccadic accuracy. This result is not consistent with perceptual localization tasks, where increasing processing time can improve perceptual judgments (Pizlo et al., 1995). These inconsistent results may be due to using different streams of visual information for saccades and for perceptual localization (Goodale & Milner, 1992). Alternatively, perceptual localization in Pizlo et al.'s perceptual task involved judgments of the spatial separation of two targets, whereas for the saccadic task, it may be that "absolute" location on the retina of each target is relevant. It is also possible that the trade-off found in Pizlo et al.'s perceptual task occurs in the decision stages, where the mechanisms have to cope with, among other things, effects of uncertainty about target size and location. Finally, if the latency/accuracy trade-offs in the perceptual task involved event occurring within period of time much shorter than typical pauses between saccades, a trade-off would not expected to be found in the saccadic task with the longer pause duration.

There was other evidence that subjects choose not to prolong scanning time in order to improve precision. The landing variability increased when the target separation increased even after secondary saccades. This effect of target separation was not expected because presumably subjects could make additional secondary saccades to correct errors. Our subjects did make additional secondary saccades (Experiment 2) but not enough to abolish the effect of target separation on landing scatter. This implied that there was an adjustment in criterion for what defined an acceptable "in target" saccade, with the criterion scaling up for longer separations: when target separation increased, subjects scaled up the zone of acceptable landing location, preferring instead to accomplish the task faster, rather than with best possible accuracy.

The finding that extra planning time did not benefit saccadic accuracy is inconsistent with a conclusion of Kowler and Blaser (1995). They found that the saccadic spatial performance with unpredictable target step displacement can be extremely good when there is no time pressure to respond (the saccadic variability was only about 5-6 % target eccentricity). They proposed that the low landing variability may be due to a strategy of waiting long enough until the uncertainty of target location was reduced. In the present experiments, where uncertainty about target location was minimized, we did not find that waiting longer improved saccadic accuracy for sequence of saccades. It is possible saccades would benefit from prolonging planning time if the additional planning time can improve the visual representation, or if subjects were explicitly requested to do so. Note that in cases where saccadic targets are surrounded by distracters, increased latencies (planning time) does improve accuracy in the sense of reducing influence of distracters (Cohen et al., 2007; Coeffe & O'Regan, 1987; Ottes et al., 1985) or reducing biases due to past history. On the other hand, extra planning time (longer latencies) were not helpful in the case studied by Jin & Reeves (2009), who found that saccadic accuracies were nearly identical across different latency conditions in a study of the saccadic gap effect.

For sequences of saccades, even with sufficient available scanning time, making secondary saccades was the preferred, and maybe the only way to improve saccadic accuracy. These results may mean that longer planning time cannot help saccadic accuracy. The inevitable landing position error of primary saccades may reflect the spatial limitations of the saccadic system. It is also possible that, in order to reach the same level of saccadic accuracy, making secondary saccades is much easier and less effortful than planning more accurate primary saccades. This strategy is similar to the finding of Araujo et al., 2001, where subjects preferred to make a saccade to the closer location (even the target located at farer location) then make an additional, corrective saccade if needed, rather than processing available cuing information before executing the first saccade. Thus, one possible explanation for our result is that, when subjects are given extra time to scan, they choose not to use the time to plan, but just wait, and later, make secondary saccades if needed.

6.4. Overlap of the planning of secondary saccades to one target and primary saccades to the next target

Dwell times increased when secondary saccades occurred. The increase in dwell times (50-75 ms), however, was not as long as the typical saccadic latency. These insufficient increases suggest that the planning of primary and secondary saccades was not strictly serial, but it was not strictly parallel (and independent) either. Otherwise, there would be no increase at all. It is more likely that there was an overlap in the planning of saccades (McPeek et al., 2000). The overlap could have involved the planning of the secondary saccade to target N and the planning of the next primary saccade to N+1. In addition, the planning of the secondary saccade to a given target could have started before the execution of the primary saccade (Becker & Fuchs, 1969). This overlapped planning involved the planning of saccades to two different targets. In dwells containing secondary saccades, the following primary saccades to the next target had a short latency (time from offset of secondary saccades to onset of the next primary saccade, Fig. 8). These results imply that, when secondary saccades occurred, the overlapped planning during the dwells includes the planning of the secondary saccade to correct the current residual error by respect to the target (N) and the planning of the primary saccade to arrive the next target (N+1).

6.5. Summary

Our results show that the trade-offs between time and accuracy can also apply to sequences of saccades, consistent with Fitts's Law. That is, speed/accuracy trade-off could apply to sequence of saccades. The higher level of required precision, the longer the scanning time. Unlike other motor behaviors, this trade-off was mainly due to the occurrence of secondary saccades, rather than to increased time for planning the primary saccade. The longer planning time did not improve saccadic accuracy. This suggests that latency/accuracy trade-offs, at least in present task, do not apply to saccades. This study, to our knowledge, is the first to show the relation among saccadic planning time, saccadic accuracy and target spatial scale. It may reveal the strategy we use in natural scanning: instead of mainly adjusting saccadic latency, people would rather use more secondary saccades to achieve better accuracy, or would choose abandon the option of secondary saccades in order to minimize total scanning time.

Table 1

Combinations of Target separation (S) and target diameter (D) for Experiment 1

S (minarc)	D (minarc)	ID= $log_2 (2S/D)$
64	15	3.09
	45	1.51
127	15	4.08
	45	2.50
	90	1.50
255	15	5.09
	45	3.50
	90	2.50
	180	1.50

Table 2

Combinations of target separation (S) and target diameter (D) for Experiment 2

S (min arc)	D (min arc)	ID= $log_2 (2S/D)$
64	15	3.09
127	15	4.08
	45	2.50
256	15	5.09
	45	3.51
	90	2.51
512	15	6.09
	45	4.51
	90	3.51
	180	2.51

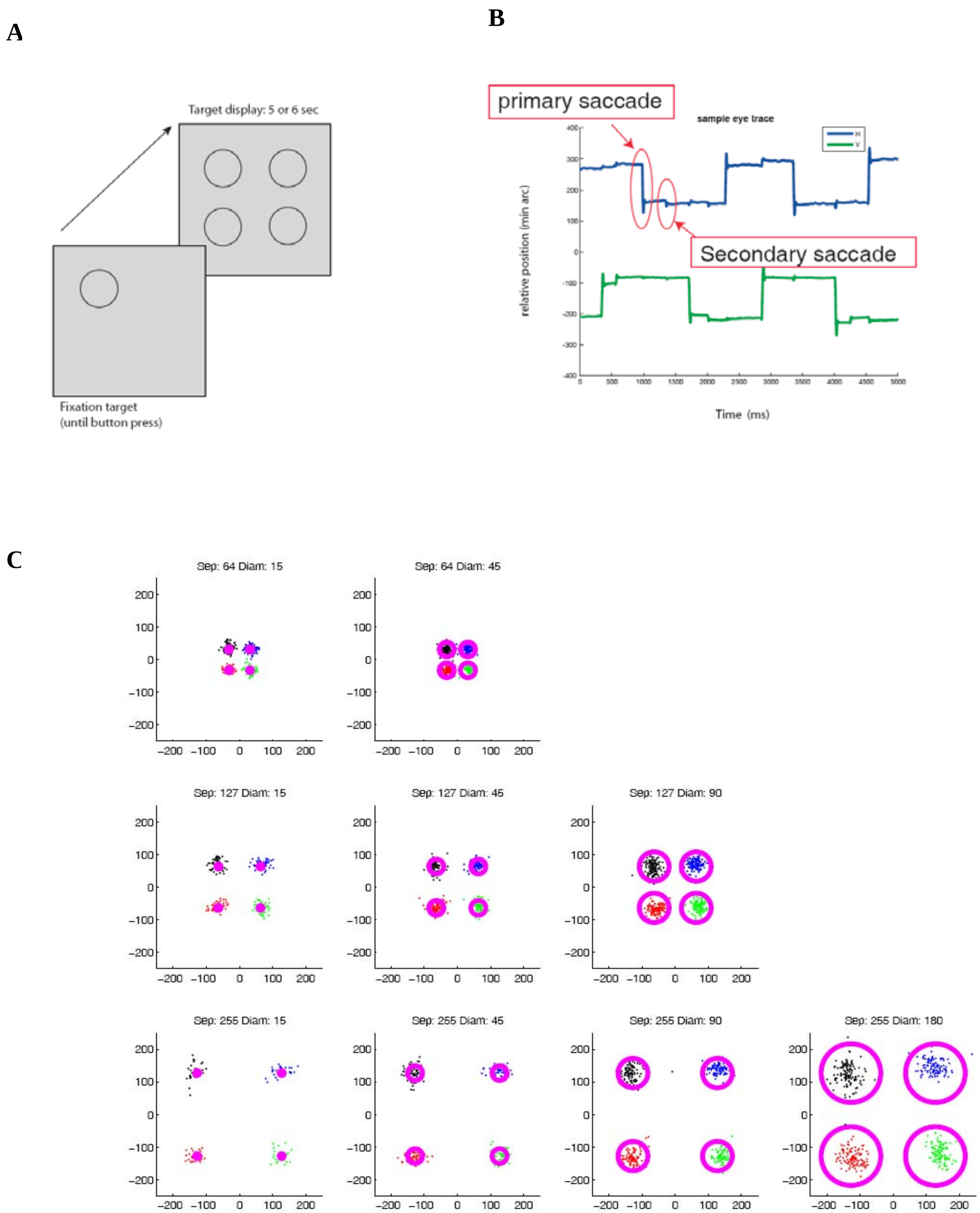

Figure 1. A: Sequence of frames in a trial. The first frame contained the fixation circle and the second frame the experiment display. B: Sample eye trace. Blue line represents horizontal eye position and green line represents vertical eye position. This eye trace shows an example of a secondary saccade following the primary saccade. C: Representative endpoints of primary saccades from subject JW superimposed on displays of 4 targets for each target separation and diameter.

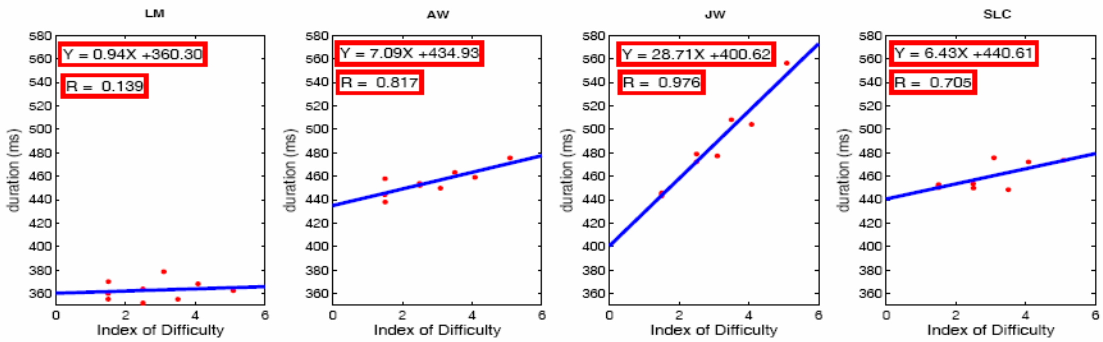

Figure 2. Mean time per segment of a loop as a function of the Index of Difficulty(ID) where ID is defined as $log_2 (2S / D)$, with S the separation and D the target diameter. Data from 4 subjects. Each datum point is based on approximately 640-1150 observations.

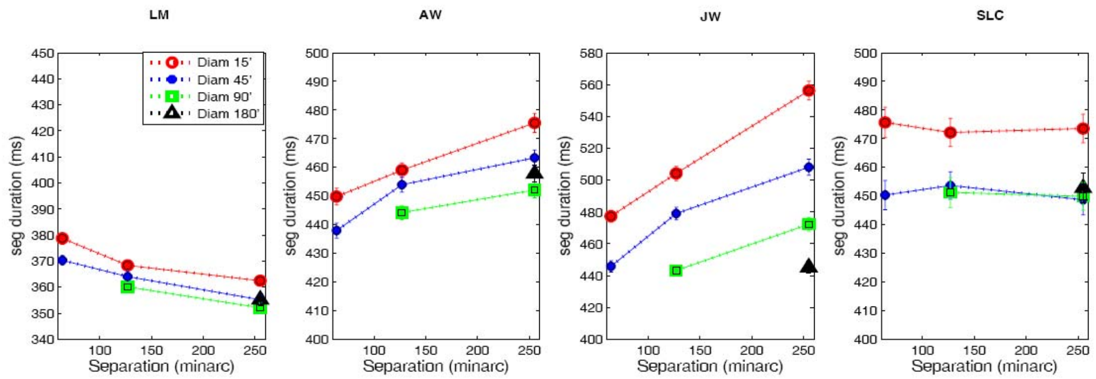

Figure 3. Mean time per segment as a function of target separation for different target diameters. Bars show +/- 1 SE; otherwise SE's are smaller than the plotting symbols. Each datum point is based on approximately 640-1150 observations.

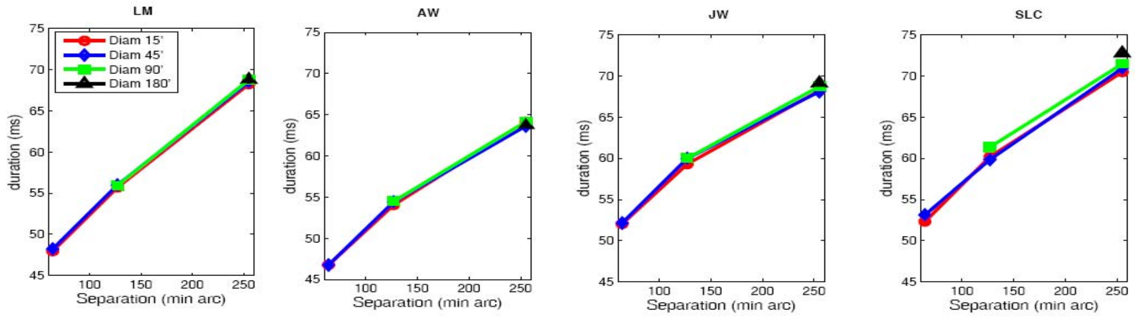

Figure 4. Mean saccadic duration, measured from the onset of the saccade to the offset, including any overshoots, as a function of target separation for the different target sizes. Standard errors are smaller than the plotting symbols. Each datum point is based on approximately 640-1150 observations.

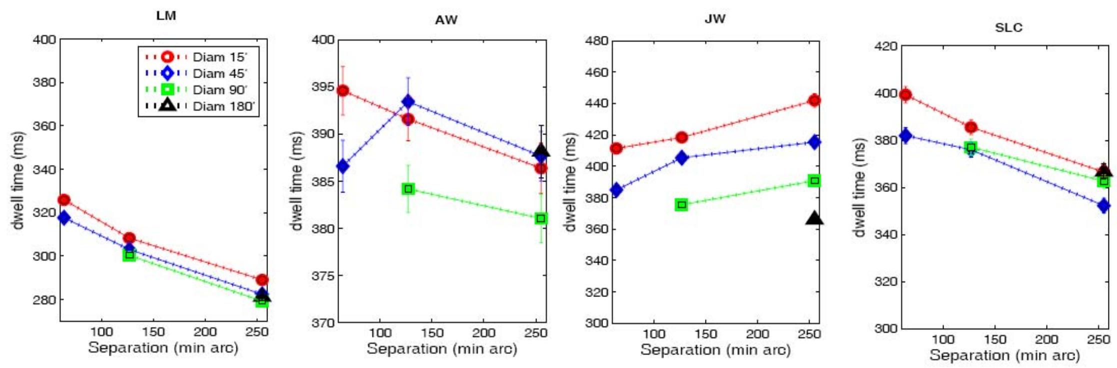

Figure 5. Mean dwell time as a function of target separation for different target sizes. "Dwell time" was defined as the time between successive primary saccades (excludes duration of secondary saccades). Bars show +/- 1 SE; otherwise SE's are smaller than the plotting symbols. Each datum point is based on approximately 640-1150 observations.

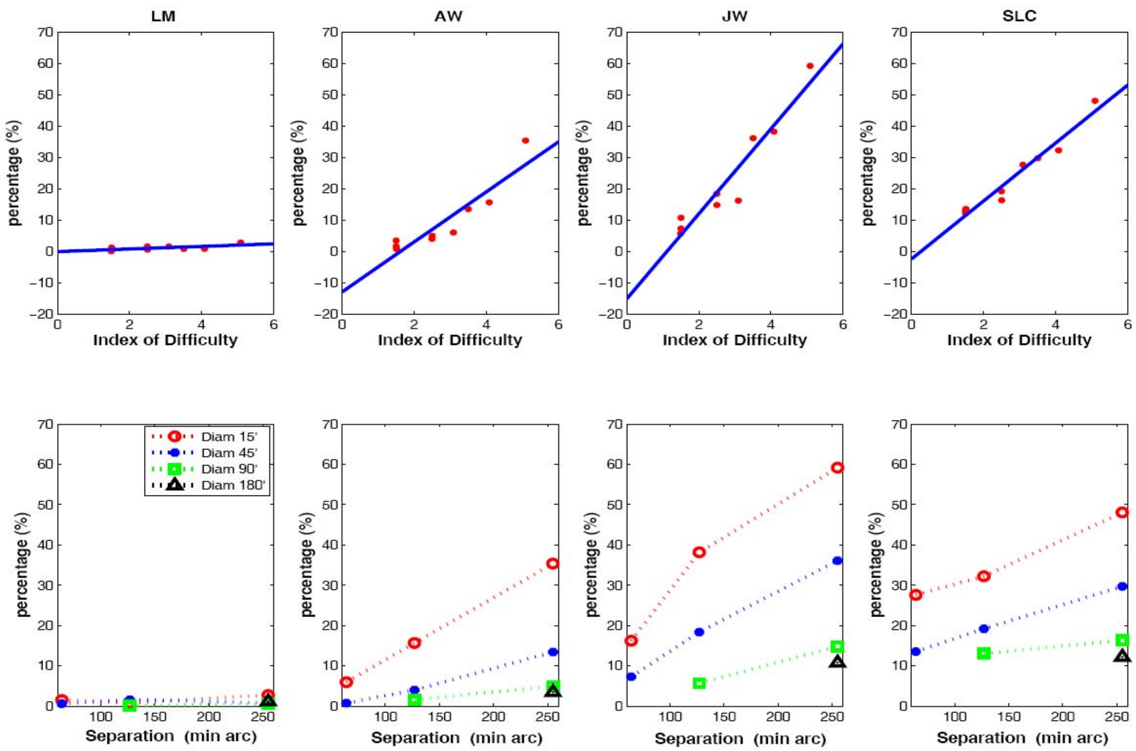

Figure 6**.** Top: Frequency of secondary saccades as a function of the Index of Difficulty. Bottom: Frequency of secondary saccades as a function of target separation for different target sizes. LM rarely made secondary saccades. Each datum point is based on approximately 640-1150 observations.

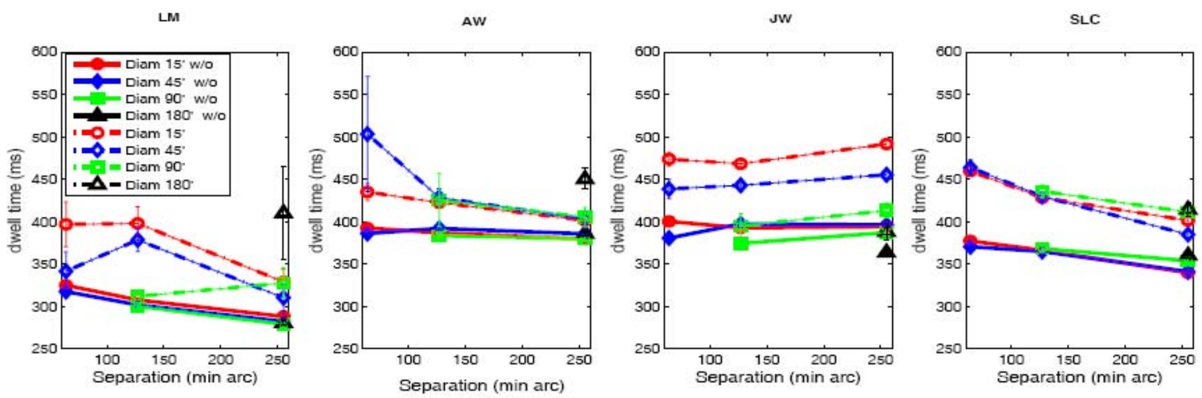

Figure 7. Mean dwell times with (dashed line) and without (solid line) secondary saccades as a function of target separation for different target sizes. Bars show +/- 1 SE; otherwise, SE's are smaller than the plotting symbols.

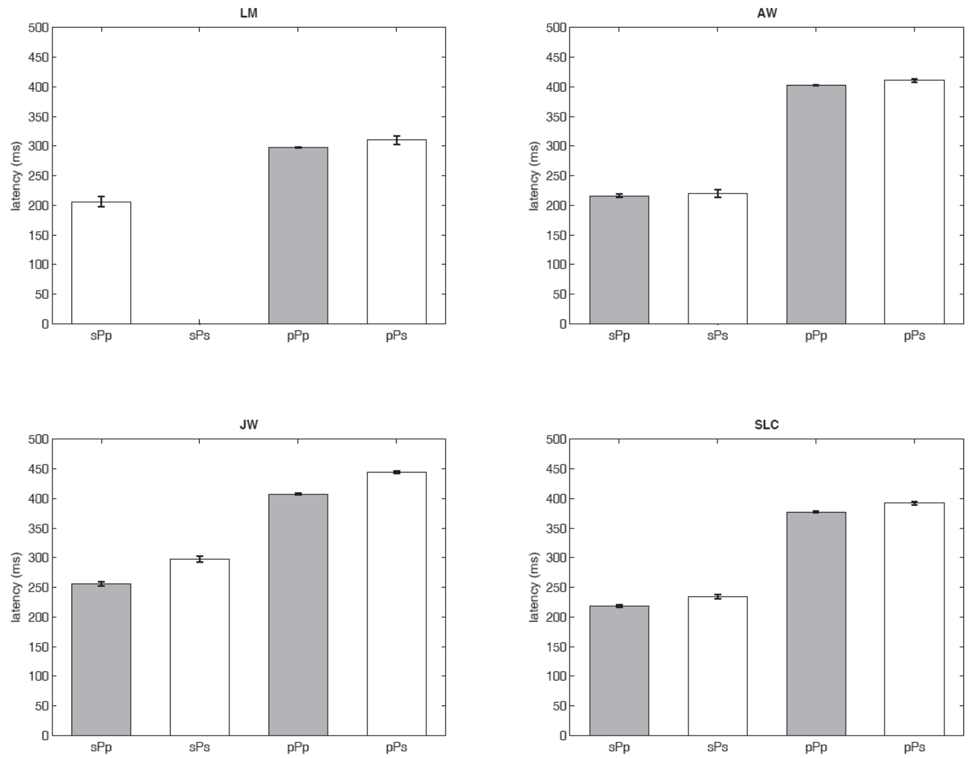

Figure 8. Mean latency (+/- 1 SE) of the four categories of primary saccades collapsed across all target sizes and separations. Subject LM did not have any saccades in the sPs category. Bars are +/- 1 SE.

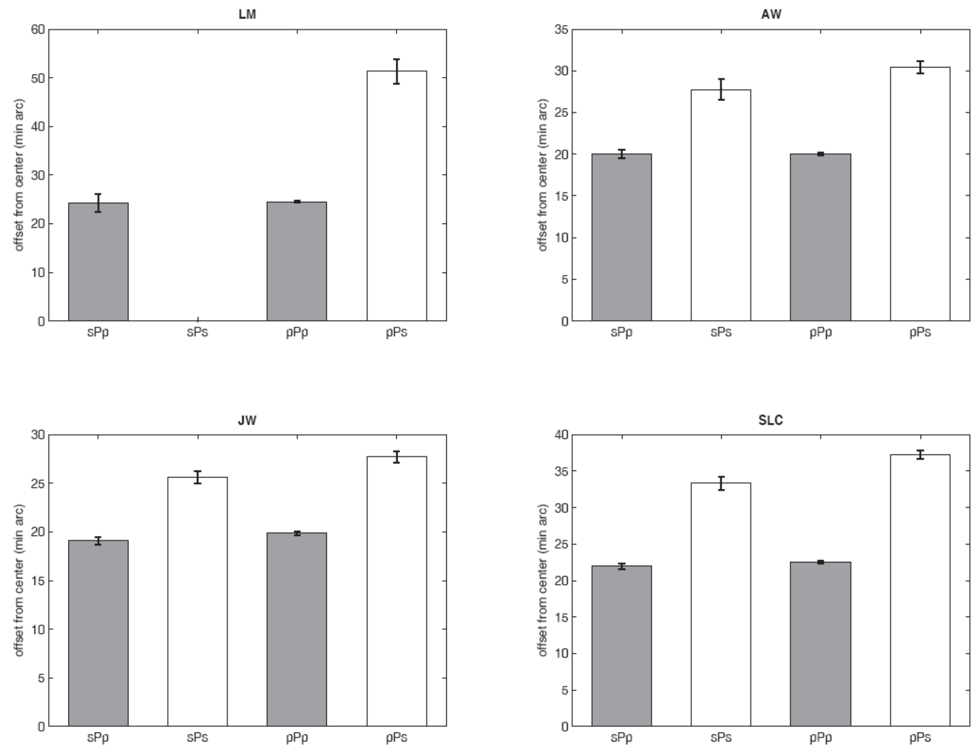

Figure 9. Mean offset of primary saccadic endpoints from target center (+/- 1 SE) for the four categories of primary saccades collapsed across all target sizes and separations. Subject LM did not have saccades in the sPs category. Bars are +/- 1 SE.

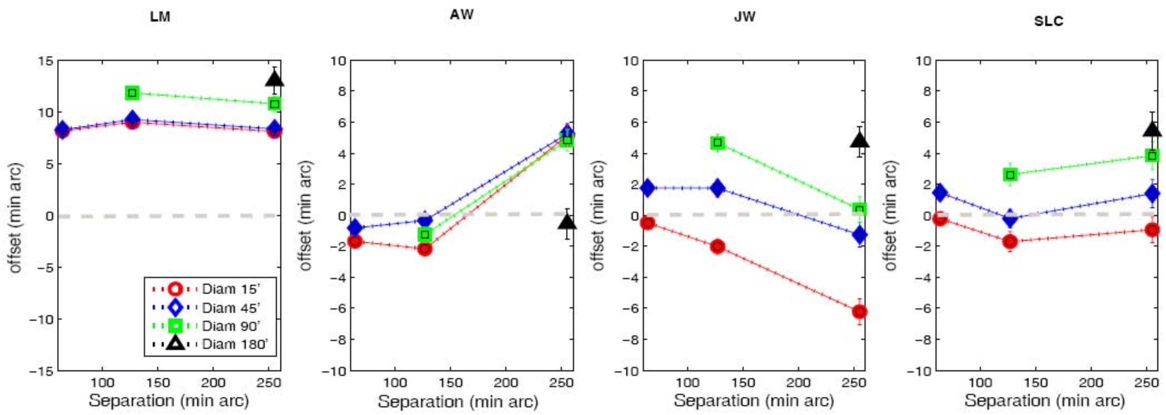

Figure 10. Mean offset of endpoint of primary saccades relative to target center along the principal meridian of the saccade as a function of target separation for the different target sizes. When primary saccades fell short of the target (undershoots), the offset was signed negative; otherwise, the offset was signed positive. Bars show +/- 1 SE; otherwise, SE's are smaller than the plotting symbols. Each datum point is based on approximately 640-1150 observations.

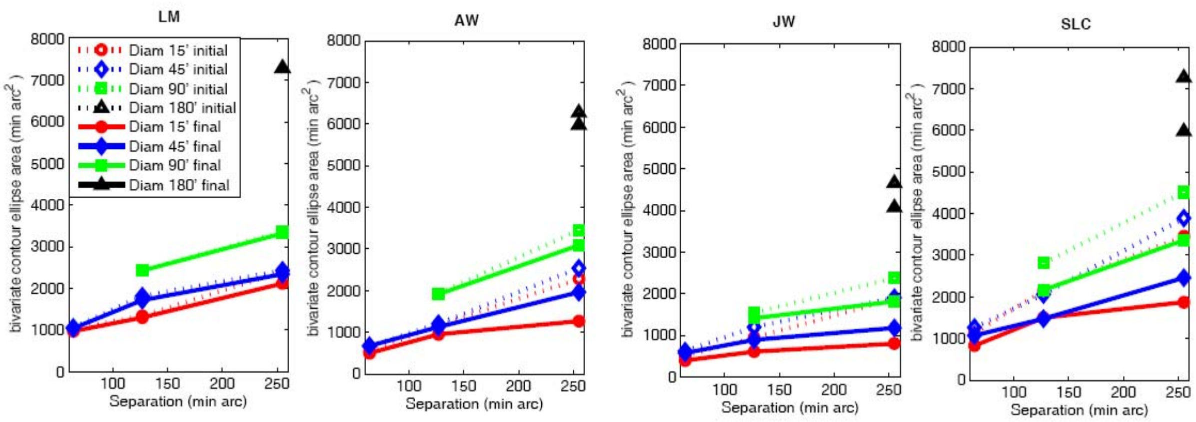

Figure 11. Bivariate Contour Ellipse Area (measure of 2D scatter) for initial (primary) saccades (dashed line) and the final saccade following any secondary saccades (solid line) as a function of target separation for the different target sizes. Each datum point is based on approximately 640-1150 observations.

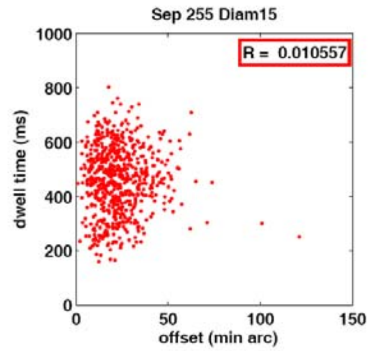

Figure 12. Representative scatter plot of initial saccades, showing dwell time and offset from center for initial saccades in the most difficult experimental condition (separation 255’, diameter 15’). Data was for subject JW and results were essentially the same for the other subjects and conditions. This scatter plot is based on 644 observations.

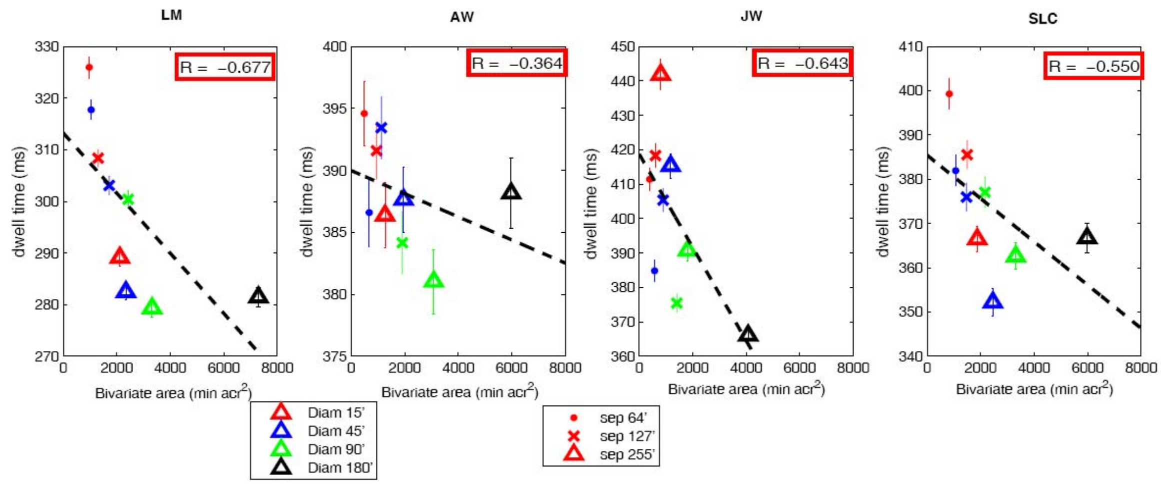

Figure 13. Mean dwell time as a function of average scatter of landing position for *final* saccades. Different colors represent target sizes. Different symbols represent target separations. Each datum point is based on approximately 640-1150 observations.

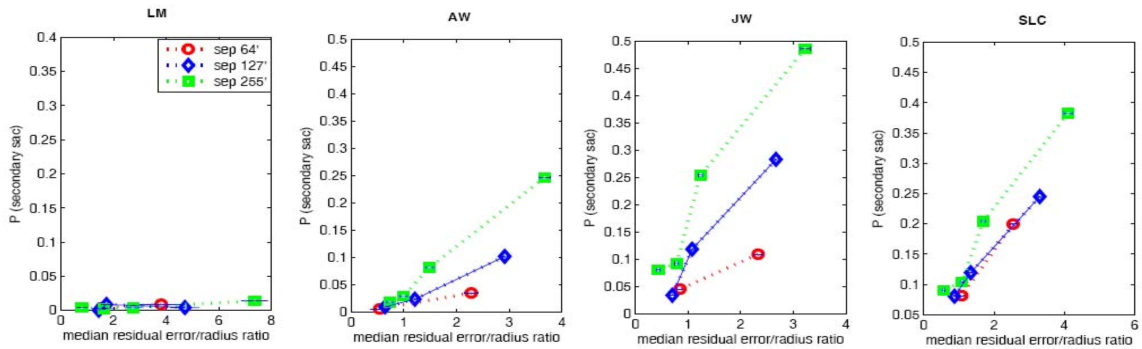

Figure 14. The frequency of secondary saccades as a function of the ratio of median landing offset of primary saccades to the size of the target for the different target separations. Horizontal error bars represent +/- 1 SE; otherwise, SE's are smaller than the plotting symbols. Each datum point is based on approximately 640-1150 observations.

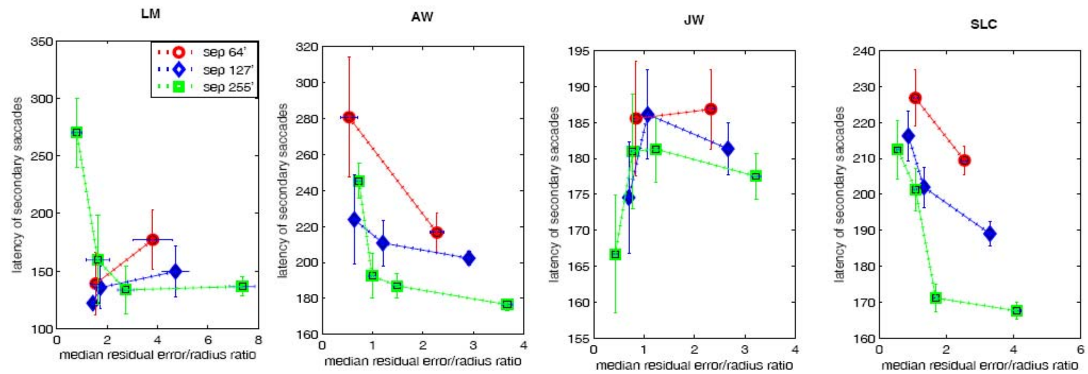

Figure 15. Mean latency of secondary saccades as a function of the ratio of the error of the primary saccade to the size of the target for the different target separations. Vertical error bars represent +/- 1 SE of latency of secondary saccades and horizontal error bars represent the +/- 1 SE of the ratio. Each datum point, except for LM, is based on approximately 6-619 observations.

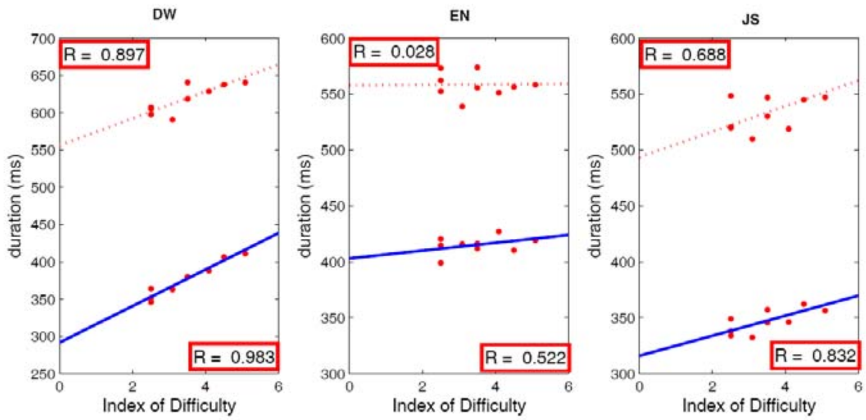

Figure 16. Mean time per segment of a loop as a function of the Index of Difficulty(ID) in fast (solid line) and slow (dash line) conditions for three subjects in Experiment 2. Each datum point is based on approximately 340-500 observations.

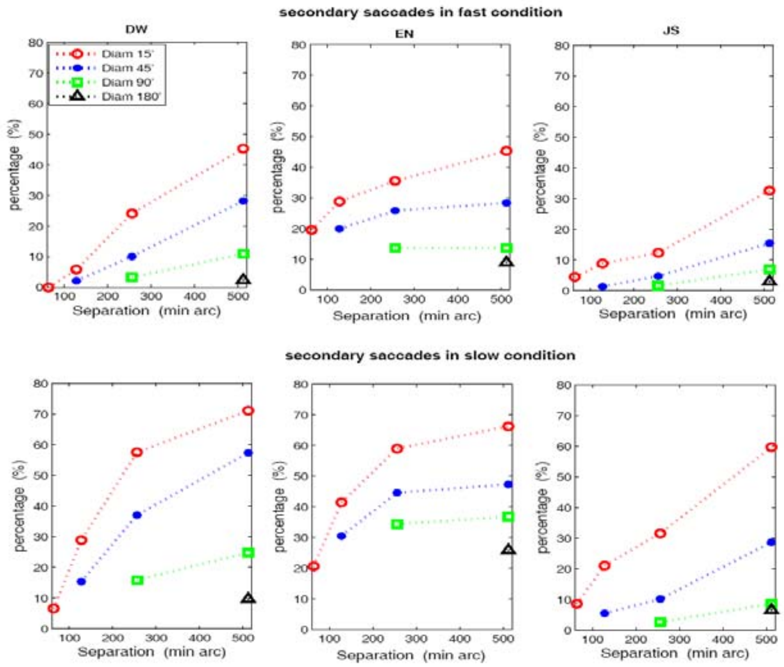

Figure 17. Frequency of secondary saccades as a function of target separation for the different target sizes for fast (top) and slow (bottom) conditions in Experiment 2. Each datum point is based on approximately 340-500 observations.

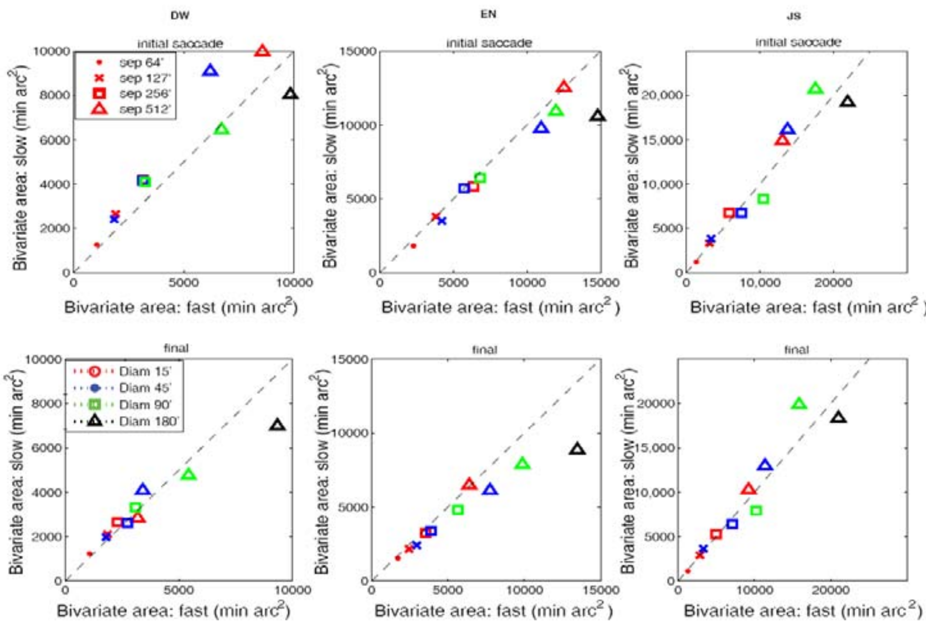

Figure 18. Bivariate contour ellipse area (a measure of the scatter of landing positions) in the fast vs. slow conditions, for different target sizes and separations. Top graphs: initial saccades. Bottom graphs: Final saccades. Each datum point is based on approximately 340-500 observations.

Appendices

Table A1.
Dwell time analysis & dwell time with and without secondary saccades (s) for AW

Separation	64			
Diameter	15	45	90	180
mean dwell	394.59	386.58	NaN	NaN
std	85.09	88.59	NaN	NaN
N	1100	1028	0	0
Separation	127			
Diameter	15	45	90	180
mean dwell	391.59	393.44	384.16	NaN
std	80.97	85.18	87.93	NaN
N	1236	1144	1244	0
Separation	255			
Diameter	15	45	90	180
mean dwell	386.37	387.64	381.04	388.16
std	88.69	85.03	89.57	86.84
N	1116	1040	1196	960
Separation	64			
Diameter	15	45	90	180
mean dwell w/o s	392.47	386.01	NaN	NaN
std	85.11	88.02	NaN	NaN
N	1045	1023	0	0
mean dwell with s	434.87	503.2	NaN	NaN
std	74.51	135.24	NaN	NaN
N	55	5	0	0
Separation	127			
Diameter	15	45	90	180
mean dwell w/o s	386.74	391.94	383.65	NaN
std	81.42	85.44	87.44	NaN
N	1068	1097	1229	0
mean dwell with s	422.39	428.34	425.6	NaN
std	70.88	71.09	117.79	NaN
N	168	47	15	0
Separation	255			
Diameter	15	45	90	180
mean dwell w/o s	379.59	385.64	379.87	385.94
std	91.79	85.31	89.7	86.6
N	771	919	1141	927
mean dwell with s	401.54	402.84	405.16	450.3
std	79.38	81.56	83.96	69.58
N	345	121	55	33

Table A2.

Dwell time analysis & dwell time with and without secondary saccades (s) for JW

Separation	64			
Diameter	15	45	90	180
mean dwell	411.35	384.85	NaN	NaN
std	103.01	92.2	NaN	NaN
N	932	892	0	0
Separation	127			
Diameter	15	45	90	180
mean dwell	418.29	405.35	375.43	NaN
std	108.64	100.15	85.29	NaN
N	928	872	1012	0
Separation	255			
Diameter	15	45	90	180
mean dwell	441.83	415.29	390.73	366.1
std	111.32	95.14	89.86	82.66
N	644	712	792	928
Separation	64			
Diameter	15	45	90	180
mean dwell w/o s	400.24	380.63	NaN	NaN
std	100.05	91.03	NaN	NaN
N	791	827	0	0
mean dwell with s	473.65	438.46	NaN	NaN
std	97.34	90.82	NaN	NaN
N	141	65	0	0
Separation	127			
Diameter	15	45	90	180
mean dwell w/o s	392.7	397.26	374.43	NaN
std	108.58	100.33	84.21	NaN
N	613	717	962	0
mean dwell with s	468.08	442.81	394.72	NaN
std	89.99	90.59	103.16	NaN
N	315	155	50	0
Separation	255			
Diameter	15	45	90	180
mean dwell w/o s	394.09	396.15	387.08	363.63
std	112.72	96.65	88.89	80.02
N	328	481	681	834
mean dwell with s	491.39	455.17	413.15	387.96
std	85.27	78.23	92.9	101.02
N	316	231	111	94

Table A3.
Dwell time analysis & dwell time with and without secondary saccades (s) for SLC

Separation	64			
Diameter	15	45	90	180
mean dwell	399.26	381.94	NaN	NaN
std	115.37	113.51	NaN	NaN
N	1104	1096	0	0
Separation	127			
Diameter	15	45	90	180
mean dwell	385.53	375.96	377.04	NaN
std	104.47	113.55	116.66	NaN
N	1104	1296	1164	0
Separation	255			
Diameter	15	45	90	180
mean dwell	366.5	352.19	362.59	366.75
std	103.75	104.63	109.13	104.13
N	1244	1112	1312	976
Separation	64			
Diameter	15	45	90	180
mean dwell w/o s	377.21	370.43	NaN	NaN
std	114.17	110.43	NaN	NaN
N	808	961	0	0
mean dwell with s	459.47	463.81	NaN	NaN
std	95.59	101.17	NaN	NaN
N	296	135	0	0
Separation	127			
Diameter	15	45	90	180
mean dwell w/o s	366.24	364.86	368.08	NaN
std	108.32	115.97	117.65	NaN
N	761	1074	1010	0
mean dwell with s	428.3	429.66	435.82	NaN
std	80.4	82.16	90.39	NaN
N	343	222	154	0
Separation	255			
Diameter	15	45	90	180
mean dwell w/o s	339.71	341.05	353.9	360.02
std	106.82	109.59	111.18	105.2
N	704	829	1113	855
mean dwell with s	401.41	384.84	411.21	414.28
std	88.22	80.22	81.49	82.15
N	540	283	199	121

Table A4.
Regression analysis of dwell times and vector errors for subject JW.

		R^2	P	a0	a1	a2	a3	N
separation	**diameter**							
64	15	0.01	0.22	418.64	1.81	1.19	0.10	808
	45	0.01	0.15	418.11	-0.33	-0.27	-0.01	777
127	15	0.02	0.01	414.49	1.95	0.83	-0.05	793
	45	0.01	0.02	436.86	-0.08	0.29	-0.03	756
	90	0.03	0.00	422.36	-1.30	-0.22	0.01	883
255	15	0.01	0.05	469.14	0.66	-0.55	0.00	532
	45	0.00	0.58	460.21	-0.68	-0.79	0.03	611
	90	0.01	0.10	406.44	0.59	0.20	-0.02	687
	180	0.02	0.00	386.57	0.06	0.27	-0.01	806

Y=a0 + a1(X1) + a2(X2) + a3(X1*X2);
Variable X1 was the vector error of current primary saccades (i-1) and Variable X2 was the vector error of subsequent primary saccades (i). Dependent variable Y was dwell time (i).

Fig. 12 showed no relation between the dwell time and the accuracy of primary saccades. Dwell time, however, may be devoted to two activities: planning any possible secondary saccade, and planning the next primary saccades. This relation can be represented by the formula: Dwell = C + P, where C is time for planning the secondary saccade, and P is the time for planning the next primary saccade. Given this assumption, the dwell time may be related to both the error of the current primary saccade, as well as the error of the subsequent primary saccade. Specially, time C might vary with the vector error of the previous primary saccade (N), (larger error requiring more time for a correction). Time P would vary with the vector error of next primary saccade (N+1), (more planning time results in more accurate saccades). Thus, C could be regarded as a function of the vector error of the primary saccade N (E_n), and P as a function of vector error of primary saccade N+1 (E_{n+1}). We used both variables (E_n) and (E_{n+1}) in a linear regression analysis to predict the total dwell time of saccade N+1. Table A1 shows the result of the regression analysis for subject JW. (The other subjects had similar results.) The regression analysis shows that these two vector error variables were not able to predict the dwell time. Thus, even after taking correction time into account, there was no support for the view that longer planning times reduced the errors of primary saccades. This conclusion confirms that latencies of primary saccades did not depend on whether the primary saccade was followed by secondary saccades

Table A5.
The velocity and landing offset of primary saccades followed/not followed by secondary saccades

	Pp		Ps	
		N		N
Average Velocity				
LM	3.85	949	4.38	27
AW	4.11	722	4.04	394
JW	3.74	263	3.64	381
SLC	3.76	625	3.65	619
Average landing offset				
LM	22.05		57.76	
AW	18.86		30.11	
JW	19.23		26.17	
SLC	21.38		34.98	
R				
LM	0.14		0.06	
AW	0.22		0.2	
JW	-0.04		-0.34	
SLC	-0.01		0.13	

Pp: Primary saccades followed by anther primary saccade.
Ps: Primary saccades followed by secondary saccades.

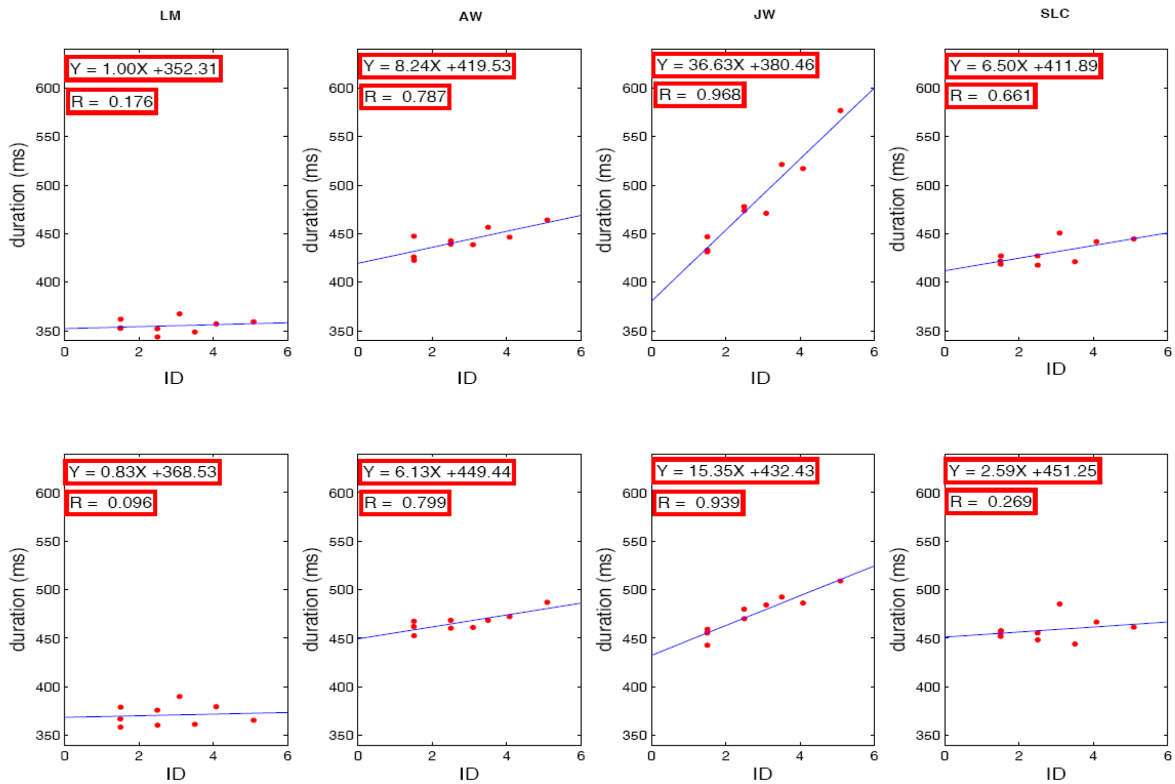

Fig. A1. Mean time per segment of a loop as a function of the Index of Difficulty(ID) for the first loop (upper) and for the second loop (lower). Data were from 4 subjects. Fitts's Law holds for both first and second loops with effects larger in the first loop.

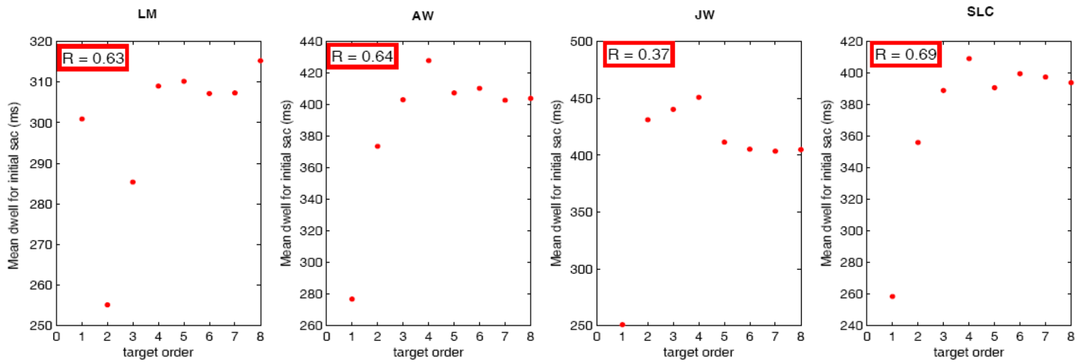

Fig. A2. The average dwell time as a function of ordinal positions of targets in the sequences of two loops. Note that for the first loop, dwell time increased with the order of positions. The same pattern did not happen in the second loop.

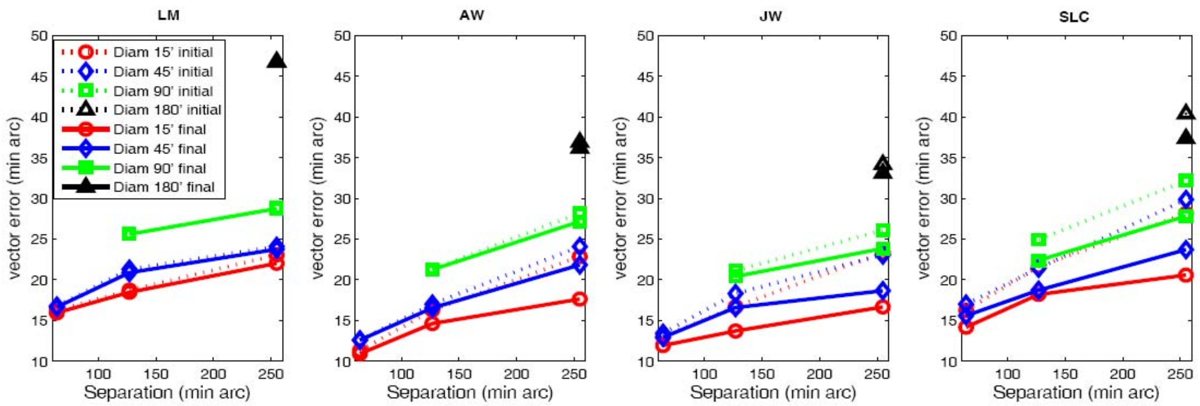

Fig. A3. Mean offset from center for initial saccade reaching the target (dashed line) and the final saccade following any secondary saccades (solid line) as a function of target separation for the different target sizes. Standard errors are smaller than the plotting symbols. The pattern of results is the same as obtained from analysis of 2-dimensional scatter of landing positions (Fig. 11).

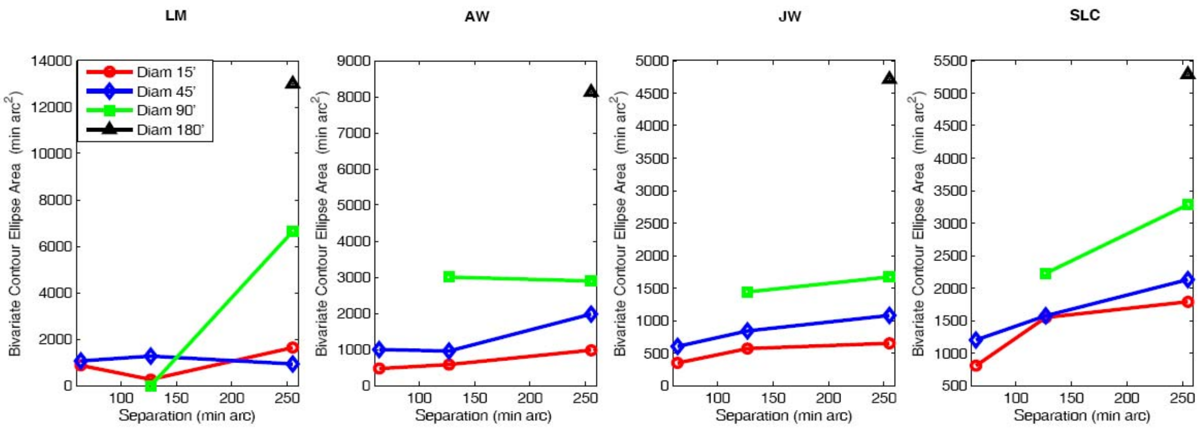

Fig. A4. Mean scatter of the offset position of secondary saccades as a function of target separation for different target sizes. (These data are a subset of those included in Fig. 11, "final" saccades.) The increase in scatter with increasing target separation for the final saccades (Fig. 11) was not only due to the subset of final primary saccades, but also to the secondary saccades. The analysis of secondary saccades shows that the scatter of secondary saccades increased with target separation and with size.

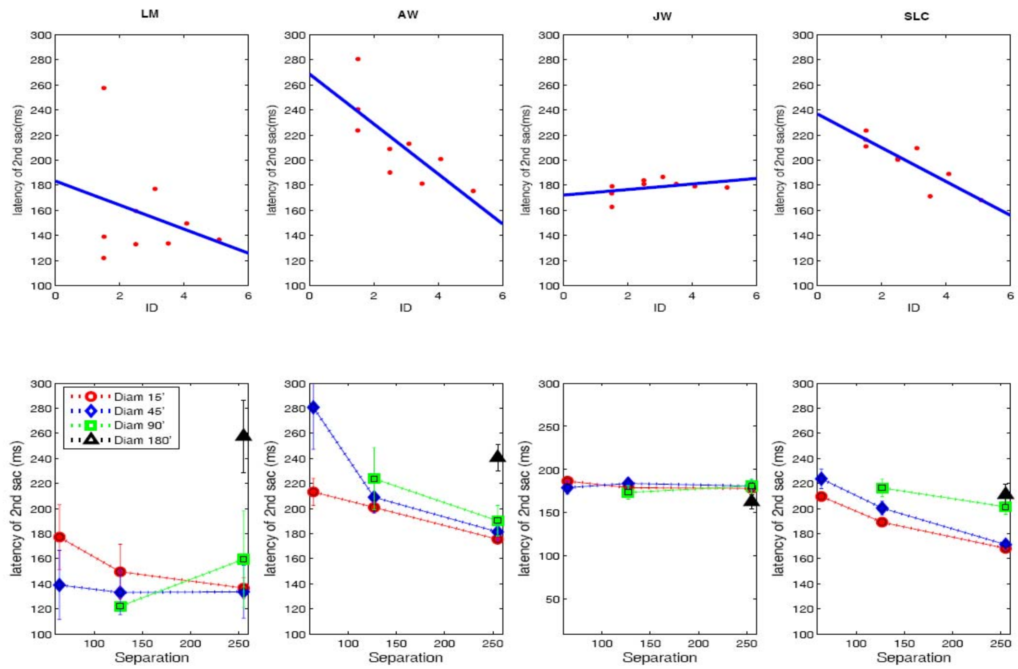

Fig. A5. The average latency of secondary saccades as a function of target separation for different target sizes. Error bars represent +/- 1 SE. Note that the latency of secondary saccades was shorter for the more difficult (larger value of ID) cases (larger separations, smaller sizes) where secondary saccades were also more frequent (see Fig. 6). This held for all subjects except JW, whose secondary saccade latencies did not vary appreciably with ID. The pattern of results is consistent with Fig. 15, which shows the latency of secondary saccades as a function of the ratio of retinal error following the primary saccade to the radius of the target.

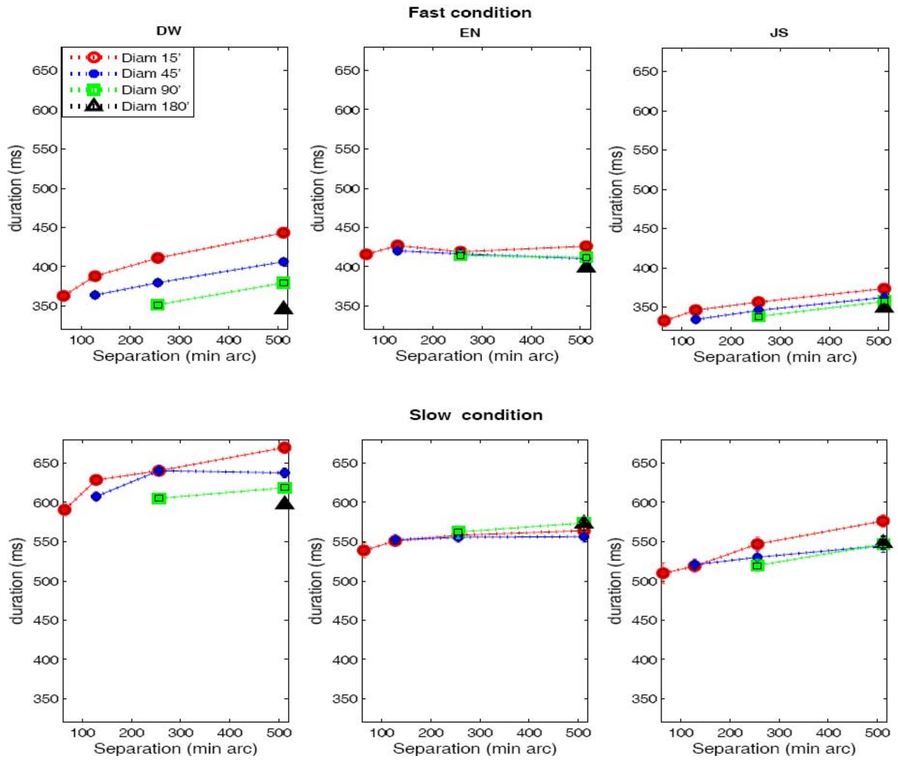

Fig. A6. Mean time per segment as a function of target separation for different target sizes for Experiment 2. Upper graph was for the fast condition and lower graph was for the slow condition. Standard errors are smaller than the plotting symbols. Data were from three subjects. As in Experiment 1, time/segment was longer for smaller targets and, for two subjects (DW and JS), for larger target separations

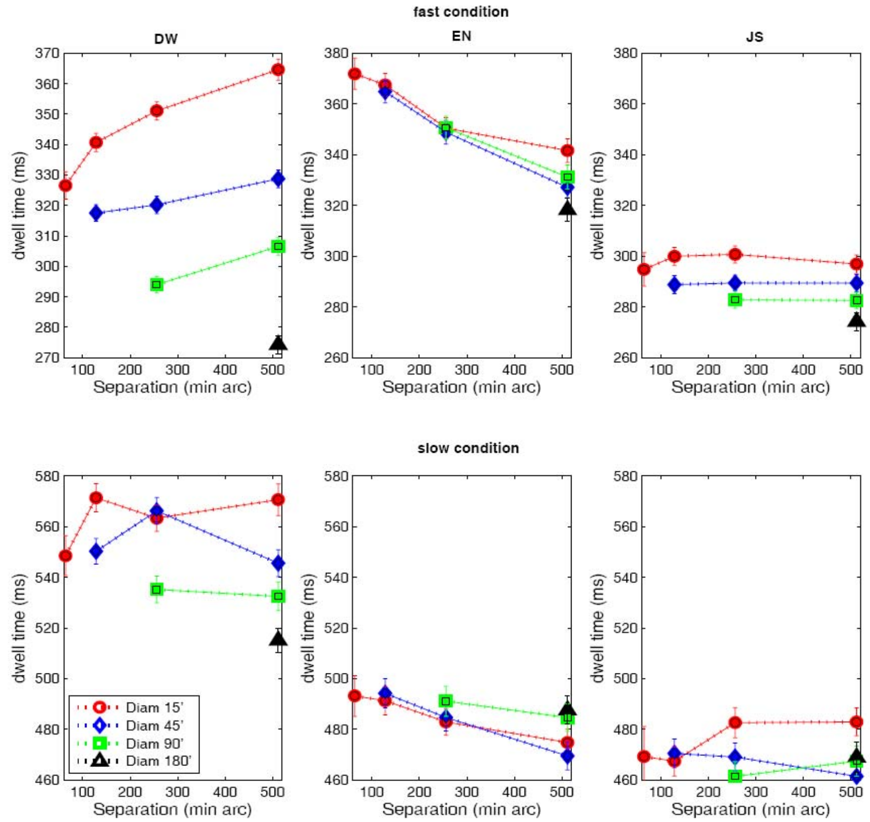

Fig. A7. Mean dwell time as a function of target separation for different target sizes. Upper graph was for the fast condition and lower graph was for the slow condition. The pattern of dwell times in Experiment 2 were similar to those in Experiment 1 in that dwell times were longer for the smaller targets, while the effect of separation varied across subjects

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