TIMING OF SACCADIC EYE MOVEMENTS IN AN ACCUMULATIVE VISUAL SEARCH TASK

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ABSTRACT OF DISSERTATION

Timing of saccadic eye movements during an accumulative visual search task

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The quality of visual performance depends on how efficiently saccades can be programmed. During each intersaccadic pause, the visual system needs to evaluate the fixated content and also determine where to look next. Most prior studies focused only on the spatial element of saccadic decisions but ignored the effect of time. A good search strategy should be able to apportion time between saccade production rate and the accuracy of target selection to maximize the acquisition of information. The current work is interested in how time is used in saccadic planning and how people decide when to look next.

To answer these questions, a novel experiment was designed where subjects were asked to search through arrays of targets (thin circles containing oriented lines) embedded in non-targets (thicker circles), either to estimate a statistical property of the targets (mean orientation of the lines), or to just look at the targets.

Varying the visual similarity of targets and non-targets had large effects on both the probability of landing on a target and the number of circles fixated per second in both estimation and the look-only tasks. Also, the eye dwelled longer on targets than on distractors even in the look-only task, where there was no need to evaluate target content.

Saccadic dwell times, however, were about the same, regardless of whether the eye moved next to a target or to a distractor.

The results show that the timing of saccades depends on (1) the currently fixated content, (2) accumulated evidence in eccentric vision and also (3) an internal timer. The strategy, which incorporates these three factors rather than simply relies on any one of them, may guarantee efficient use of time in saccadic planning.

Acknowledgements

First and foremost, I would like to thank my advisor, Eileen Kowler, who not only invested enormous time and energy in this work but also provided her invaluable guidance and tireless support through my graduate school years. I would also like to thank the members of my dissertation committee, Jacob Feldman, Manish Singh, and Michele Rucci for providing incredibly helpful suggestions in this work. I also wish to thank John Wilder, Brian Schnitzer, Elio Santos, Nick Ross, Min Zhao and Cordelia Aitkin for sharing their wisdom. Finally, I would like to thank my parents and siblings for their continuous support, encouragement and love.

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1. Introduction

Saccadic eye movements bring the line of sight to informative and useful locations in the visual scene. Choices about when to initiate a saccade and where to aim the saccade are guided by visual information acquired during the brief fixation pauses between successive saccades. This study is concerned with the timing of saccadic decisions in a task that requires search through a visual array in order to estimate the statistical properties of the targets.

Observers evaluate the currently available visual information during each fixation pause to make decisions about the content of the display and to decide where to look next. Given the limited amount of available time to perform a task, an efficient strategy for deciding where to aim saccades is the one that brings gaze to informative locations and maximizes success on the task. Najemnik & Geisler (2005, 2009), for example, showed that during visual search, saccadic planning is efficient in that gaze moves to locations that result in maximum information gain. Legge, Klitz & Tjan (1997) advanced a related proposal for eye movements during reading, in which saccadic landing position was chosen to maximize the probability of recognizing each successive word.

Strategies of saccadic planning, however, also need to take into account time. In general, decisions about aiming any movement can benefit from taking more time to select the goal and plan the movement trajectory (Rosenbaum, 2009). Time may be also important for saccades because taking more time to select the saccadic goal could increase the likelihood of finding and then landing on useful objects (Araujo, Kowler, & Pavel, 2001; Cohen, Schnitzer, Gersch, Singh, & Kowler, 2007; Hooge & Erkelens, 1999; Wu, Kwon, & Kowler, 2010). However, there are tradeoffs. Taking too much time to select saccadic goals may result in longer pause durations, a lower rate of saccade production, and a net reduction in the rate of fixating interesting objects. By contrast, increasing saccade rate would increase the number of locations fixated in a given amount of time, but allowing too little time for careful saccadic planning may direct many saccades to useless locations.

A key question is how people handle the tradeoff. To what extent do people consider the value of visual information when planning saccades, balancing the need for selection of useful targets against the need to maintain an efficient saccade rate? Under conditions where useful information is either highly visible against the immediate surround, or, alternatively, in locations that are either highly familiar or easily guessed, selection of the saccadic goal will place little demand on time. The question of time (and resource) management becomes interesting under more difficult circumstances, for example, when targets do not stand out well against the background, or when prior information or context does not allow their locations to be guessed with high accuracy.

Araujo, Kowler & Pavel (2001) investigated time management in a study of the role of cues in saccadic planning. They found that subjects were reluctant to prolong saccadic latencies to take into account useful visual cues even when this information could help guide saccades to targets. Instead, most of subjects preferred to make a saccade to the least eccentric location, regardless of its utility. They suggested that the system may favor a strategy of least effort over a strategy of using available information from eccentric vision. Earlier, Hooge & Erkelens (1998) found that when the information about target location was provided by visual cues located within the stimulus elements, and subjects were explicitly asked to direct their gaze based on the cues, subjects still made about 20-35% of their saccades to irrelevant (uncued) locations. This result shows that the cues are not fully used to guide saccades even when they are directly provided to the fovea. The results mentioned above suggest that the human visual system does not favor a strategy of pausing longer to plan carefully. Instead, the strategy of rapid scanning is often preferred, even when the accuracy of selection is sacrificed as a result.

Since people do not use all the available information to guide saccades, what do they do during the fixation pause? To address this question, Hooge and Erkelens (1999) required subjects to search an array of Landolt C's for a single O-shaped target. The difficulty of distinguishing the target O from the C's was controlled by varying the size of the gap in the C's. At the same time, visual cues to the location of the target O were provided by varying the width of the line (the target O was drawn with thin line, while the outline width of C's was varied). Therefore, the difficulty of selection could be increased by making the line width of Landolt C's similar to the line width of target O. Hooge and Erkelens (1999) found that intersaccadic pause duration depended on the gap size, that is, the foveal task. Pause duration increased when gap size became smaller. Surprisingly, pause duration was not changed much when the difficulty of distinguishing possible O's and C's using peripheral vision was increased by making the line widths more similar. The results from the studies of Araujo et al. (2001) and Hooge and Erkelens (1998;1999) suggest that the intersaccadic pause interval is used mainly for analyzing the immediate visual content rather than for evaluating additional information to make a more informed decision about where to direct the upcoming saccade.

The goal of present study is to further understand the timing strategy underlying saccadic decisions by studying saccades in a statistical estimation task. A statistical estimation task (unlike a conventional search task) was tested because it encourages observers to continue making saccades in an attempt to improve performance, rather than terminating abruptly once a given target is found.

The study will focus on two questions:

1. What is the role of visual cues in the control of saccadic timing? Prior studies had shown that the control of fixation duration is affected either by the difficulty of evaluating the currently fixated item, or the expectation based on past history, but not by the difficulty of using visual cues to select potentially useful targets (Hooge & Erkelens, 1998; 1999). A good strategy, however, should not neglect the eccentric information, which can help guide saccades to important locations. How are eccentric visual cues used during saccadic planning, and what is the cost (time costs) attached to their use?
2. How do people apportion time during visual search? As mentioned above, the relevant choice is between prolonging the fixation pause to improve the accuracy of target selection, and shortening pause duration to increase the production rate of saccades. What strategy do people use during visual search to determine when to look next? Do they prefer a higher and consistent scanning rate, regardless of selection accuracy, as shown by the results of some prior studies? Or, do people prefer to fixate at the location that is most likely to contain the target without considering the cost in time?

The question of how people decide when to make saccades has been investigated over the past few years. Two different types of strategies have been proposed. The first one is an evidence based strategy in which saccadic decisions are made when the accumulated information reaches a criterion bound (Carpenter & Williams, 1995; Gold & Shadlen, 2007). This is similar to other accumulator models in non-saccadic tasks that proposed that decisions would not be made until the accumulated evidence reached the decision criterion (Brown & Heathcote, 2008; Ratcliff & Smith, 2004). The use of an accumulator is illustrated in Figure 1a for two levels of task difficulties.

Contrary to the accumulator model, which suggests that the saccadic system would keep gathering information to trigger saccades until the criterion was reached, other studies found that eccentric information in visual search tasks was underused, or even played little role in saccadic decisions. That is, the decision of when to make a saccade was not based on the level of information about target location. Hooge and Erkelens (1999) and Araujo et al. (2001) both found that the direction and the timing of saccadic decisions did not make adequate use of cues indicating the likely target location. This suggests that a deadline may determine when to make next saccade regardless of how much evidence about target location had been accumulated. Using time as the decision criterion to determine when to initiate saccades has been found by many prior studies. (Churchland, Kiani, & Shadlen, 2008; Cisek, Puskas, & El-Murr, 2009; Nuthmann, Smith, Engbert, & Henderson, 2010; Ludwig, 2009). Figure 1b illustrates this alternative.

The accumulated evidence model and the timer model make different predictions about saccadic performance when the difficulty of target selection is varied. During visual search, information about target location presumably integrates over time, and how fast the information could reach a threshold depends on the difficulty of target selection. The accumulator model would predict that a saccade would be made only when this threshold is reached. Thus, the time taken to reach the threshold should be longer when target selection becomes harder, and vice versa (see Figure 1a). The timer model, however, suggests that the saccadic decision is based on a deadline, rather than a threshold. Once the deadline is reached, a new saccade would be initiated even if there is not enough evidence to be certain about the target location. If the deadline is too short, saccadic errors are expected when target selection is hard.

Either strategy seems to impose its own cost. If time determines the decision, the available visual information may be underused and the decision made would result in a high saccade production rate, but poor accuracy of target selection. On the other hand, if the saccadic decisions were made on the basis of the accumulation of evidence (Figure 1a), the accuracy of target selection would be higher, but the cost in time may be large. Therefore, the timer model would predict effects of the level of selection difficulty on selection accuracy, while the accumulator model would predict effects of the level of selection difficulty on timing. This study aims to determine which strategy is preferred in visual search and how the timing of saccades changes accordingly.

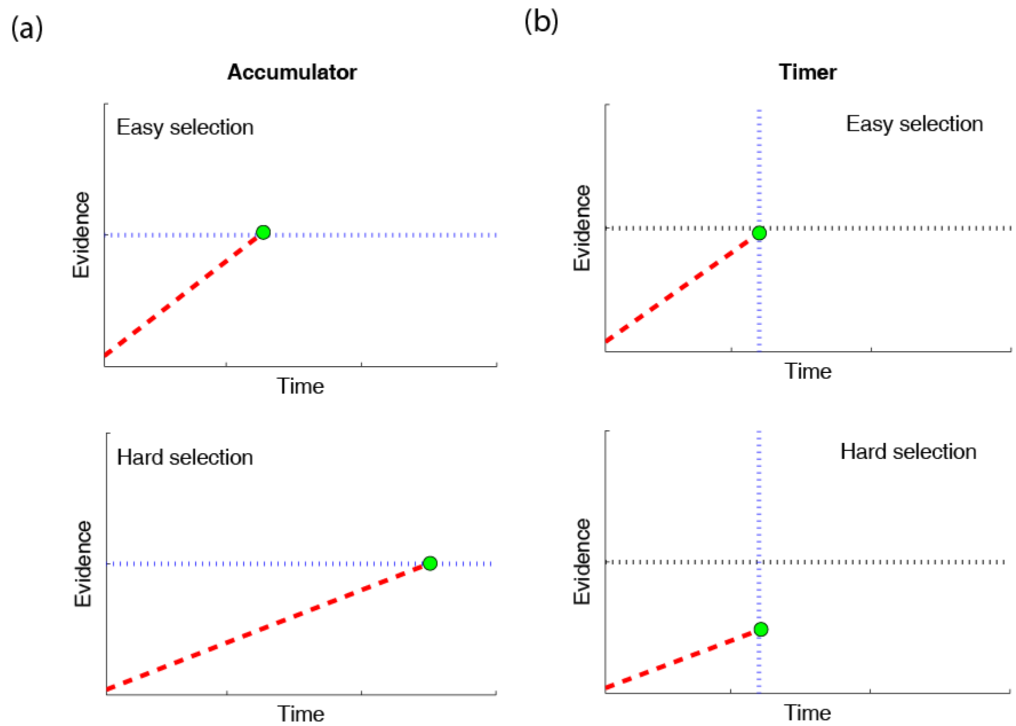


Figure 1. Two alternative models of saccadic decisions. (A) Saccadic decision based on an evidence accumulator. A saccade would be initiated when the criterion (blue line) is reached, regardless how much time it took. The decision criterion (blue line) was the criterion of evidence. (B) Saccadic decision based on an internal timer. The decision criterion (blue line) is fixed deadline. A saccade would be initiated when this deadline is reached, regardless of whether the accumulated evidence reaches the criterion (black lines) or not. The difficulty of target selection is reflected by the slopes. The evidence can be accumulated faster when target selection is easy than when target selection is hard.

The current study systematically varied the difficulty of distinguishing targets and distractors in a statistical estimation task. The task had a strong visual search component because success depended on finding several targets per trial. The main goal was to determine how the saccadic timing strategy adjusted to account for the difficulty of distinguishing targets from non-targets. In addition, performance will be compared to that in a task in which the foveal task load is reduced by asking subjects to look only at targets (no statistical estimation) and avoid looking at any non-target.

2. Methods

2.1 Subjects

Five subjects were tested (EV, KM, MJB, VK, BS). All had normal vision and no correction, and were naïve as to the experimental design and hypotheses.

2.2 Eye movement recording

Movements of the right eye were recorded by an Eyelink 1000 (SR Research) tracker (tower mount) with head held by a chin and forehead rest. Viewing was monocular with the left eye's view occluded by a patch.

2.3 Stimulus display

The stimuli were displayed on Viewsonic G90fb 19" CRT monitor at a viewing distance of 118 cm. At this distance the resolution of the display was 0.73 min arc/pixel. Displays contained 25 black (0 cd/m^2) unfilled circles (circle diameter = 30') on a white background (luminance =168 cd/m^2), arranged as shown in *Figure 2*. Six circles were defined as *target circles* drawn with a line whose width was set to 4 pixels (~2.9'). The other 21 circles were defined as distractor circles with circle outline width set to one of 3 values (5, 6 or 7 pixels). Circle width will be referred to in pixels throughout the paper. The locations of the 6 target circles were chosen randomly in each trial. The closest distance between any two adjacent circles was 150' along horizontal or oblique directions, and this distance defines the unit "separation" which will be used in the remainder of dissertation.

A thin (1 pixel wide) line (length = 0.1 deg, luminance = 33 cd/m^2) tilted about the vertical meridian was located inside each target circle. The angle of line tilt was sampled from a Gaussian distribution with mean set to one of four values (+/-30 deg; +/-10 deg), and standard deviation set to 20 deg. The angle would be re-sampled if it was not within the range between -90 to 90 deg in order to avoid confusion of tilt direction (ex. Tilt -100 deg is visually identical to tilt 80 deg). A square dot (2 pixels on a side) was located inside each distractor circle. The width of the distractor circle (5, 6 or 7) and the stimulus display duration (1s or 2 s) remained constant for the 50 trial experimental session. The numbers of target (6 targets) and distractor circles (19 distractors), the distributions of the angle of line tilt and the trial durations were all chosen on the basis of preliminary experiments so that performance on the estimation task would steadily improve with the number of target circles used during visual search.

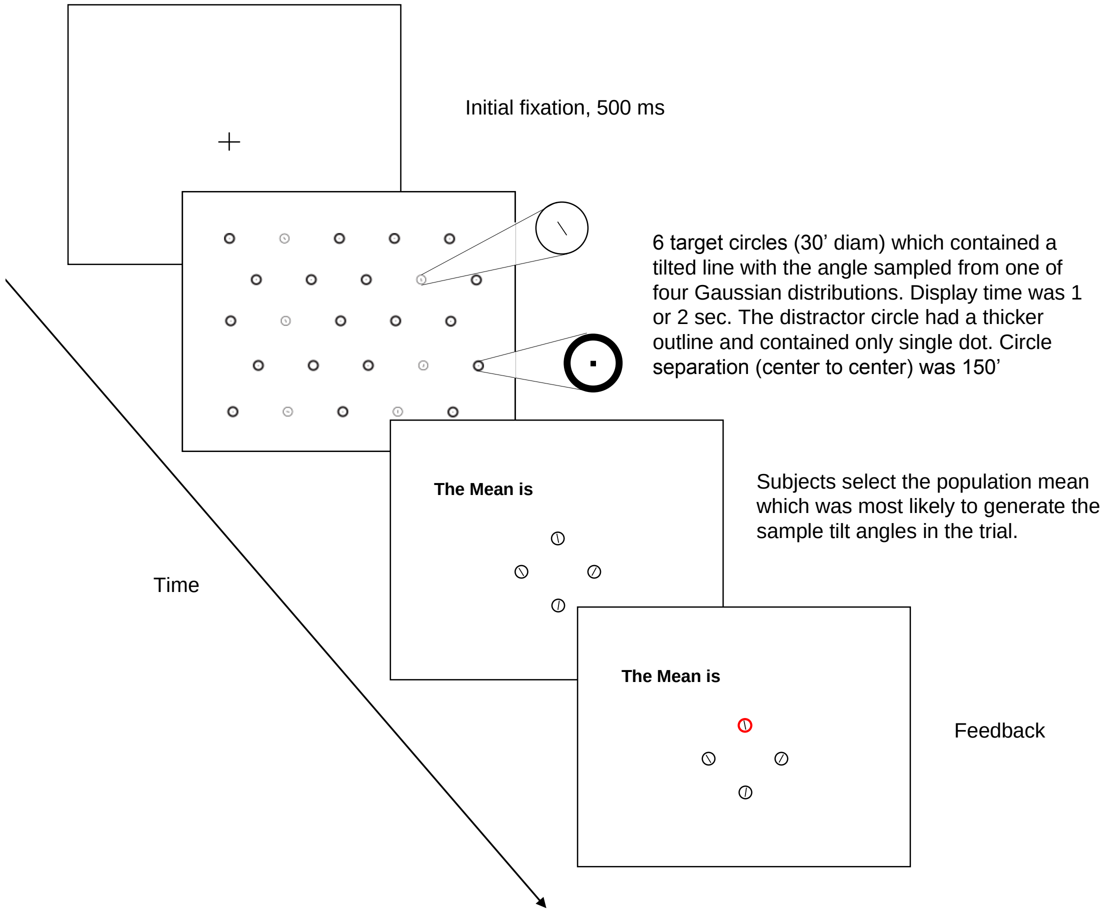


Figure 2. A sample trial of statistical estimation task.

2.4 Procedure

To examine saccadic strategies in active scanning, two tasks were tested:

(1) Statistical estimation:

A central fixation cross was displayed before each trial. Subjects fixated the cross and pressed a button to start the trial when ready. The stimulus display appeared 500 ms later and the duration of the stimulus display was either 1s or 2s. Subjects were instructed to view as many target samples as possible to estimate the mean tilt of the population from which the samples of tilted lines were drawn. After the stimulus disappeared, subjects were shown a response frame. The response frame contained 4 circles, each containing a line whose tilt was set to one of the 4 possible population means. Subjects were required to choose one of the tilts by means of a button press. They were then shown a frame containing the correct answer and noted whether their report was correct. The stimulus display and experimental procedure are shown in *Figure 2*.

(2) Look-Only:

The display was the same except that all lines within the targets had the same tilt angle, equal to one of the 4 population means. No psychophysical reports were taken. Subjects were instructed to look at as many target circles as possible and to avoid looking at any distractor circles.

2.5 Numbers of trials tested and excluded

All subjects were tested between 30 and 45 50-trial sessions. This led to a total of 1500 trials for EV, 1850 trials for KM, 1500 trials for MJB, 2250 trials for VK and 1200 trials for BS. Some trials were discarded due to loss of tracker lock during the trial (EV < 1 %; 12 % for KM; 11% for MJB; 4 % for VK and 6 % for BS).

2.6 Preliminary psychophysical testing

The following preliminary psychophysical experiments were conducted using the same stimulus display with 25 circles in order to verify the choice of stimulus parameters:

(1) The ability to discriminate the tilt of the line inside the target circle:

The size and the contrast of the tilted line within targets were each chosen so that fixation at or very near the line would be required in order to discriminate the tilt. To confirm that fixation was required a preliminary test was done. Subjects fixated a cross that was located at different eccentricities from a probe circle containing a tilted line. The eccentricity of the probe was randomly set to specified fractions of a separation (150’) of two adjacent circles (0.2, 0.4, 0.6, 0.8 or 1). Line tilt was randomly sampled from the range of -90 to 90 deg and the stimulus duration was 500 ms. *Figure 3*(a) shows that the accuracy of identifying the tilt (right/left) was over 80% correct only for eccentricities of less than half of the separation (75’) of adjacent circles. When subjects fixated on the adjacent circle (eccentricity = 150’), the accuracy was about chance level (50%). Similar results were found when the discriminability of the line tilts was easy (+/-45 deg). This shows that eccentricity should be no more than half the separation of adjacent circles to identify orientation accurately.

(2) The ability to distinguish target and distractor circles in eccentric vision:

The widths of distractor circles were chosen to sample a range of difficulty. This was confirmed in a preliminary psychophysical test. Before the trial, a fixation cross and a probe were shown on the display. The locations of fixation cross and probe were randomly selected from the locations of 25 circles so that the distance between probe and fixation cross was equal to one of three values (1, 2 or 3 circle separations, where a separation=150'). Subjects were instructed to fixate the cross through entire trial. After a button press, 12 target circles and 13 distractor circles appeared and subjects were ask to identify whether the circle at the probed location was a target (thin outline) or a distractor (thick outline). The eccentricity of the probed circle remained the same for a block of 50 trials. The duration of stimulus display was 1s. *Figure 3* (b) shows that performance, averaged over the five subjects, improved with increasing distractor width and fell as eccentricity increased, but never dropped below about 70% correct. Thus, targets and distractors were discriminable at level above chance even when target eccentricity was large. Also, the discriminability differed with distractor width.

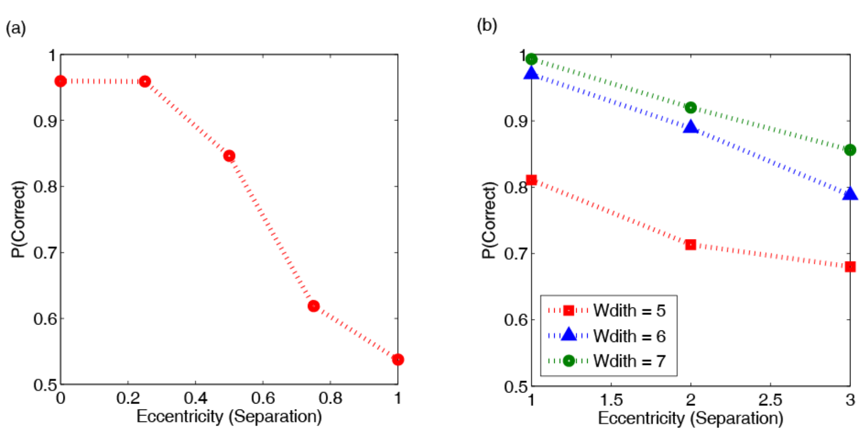


Figure 3. (a) Performance of discriminating line tilts as a function of target eccentricity. One separation was equal to the distance between any two adjacent circles and the line contrast was the same as in real experiment (Luminance=33 cd/m^2). (b) Performance of distinguishing targets and distractors as a function of target eccentricity.

2.7 Data analysis and accuracy of target selection

Saccades were detected by an algorithm that used a velocity criterion to determine saccadic onsets and offsets. Criteria were determined by examination of analog records of eye position with the onsets and offsets detected by the algorithm marked.

The proportion of saccades landing at or near targets was determined by using a nearest neighbor criterion. A nearest neighbor criterion seemed appropriate given that preliminary experiments (see *Figure 3a*) showed that the line of sight needed to be within at least a distance equal to half the separation of adjacent circles in order for the orientation of the target line to be determined with accuracy better than chance. This binary classification of landing location (target or non-target) was used to compute a measure of saccadic selectivity, defined as the number saccades landing nearest to a target divided by the total number of different circles fixated in each trial. Notice that the total number of different circles fixated is not equal to the total number of saccades because subjects may use consecutive saccades (a primary saccade followed by a secondary or corrective saccade, see below) to reach a given circle. Also, using a nearest neighbor measure of selectivity captures the effectiveness of saccades for the task, but does not mean that each saccade was assumed to be aimed specifically to either a target or a distractor circle (non-target). Saccades could have been aimed to clusters of circles (e.g., Coeffe & O'Regan, 1987) with follow-up saccades used to reach the target (Wu et al., 2010).

Saccades were also classified as "primary" or "secondary". A primary saccade was the first saccade to leave from the currently fixated circle and land on another circle using the nearest neighbor criterion. A secondary saccade was any saccade following the initial primary saccade and landing on the same circle as the preceding primary saccade. *Figure 4* shows primary saccades and secondary saccades in a sample eye trace plotted as x-y position (left) and the same trace as eye position over time (right). An additional measure, dwell time shown in *Figure 4*b, was defined as the pause interval between two consecutive primary saccades.

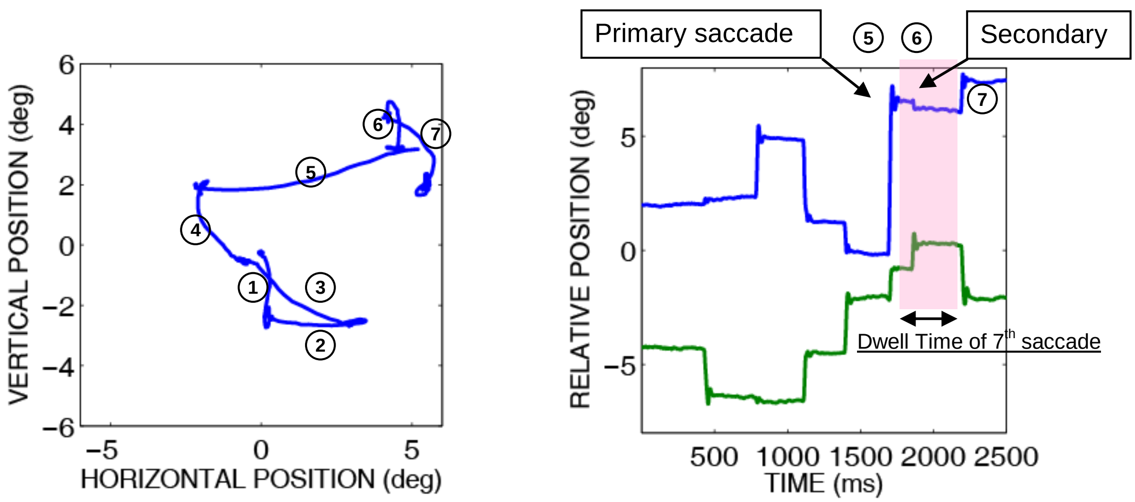


Figure 4. Sample eye trace. The left graph shows the eye positions during a single trial. The right graph shows the relative eye positions over time in the same trial. Blue line represents horizontal eye position and green line represents vertical eye position. The number on both graphs represents the order of saccades in the search sequence. The eye trace shows an example of a secondary saccade (number 6) following the primary saccade. The shaded area shows the dwell time between successive primary saccades.

To test the accuracy of the nearest neighbor criterion, given inevitable noise in the eye tracker output and the saccadic system itself, a verification test was run in which 12 target circles were randomly displayed, with the remaining 13 locations left blank. Subjects were instructed to perform an easy task: look at each target circle in a specified simple order, namely, one row at a time, scanning from left to right. They were also told to take enough time to look at each displayed circle accurately. Thus, under these conditions, performance should be nearly perfect – that is, each saccade should land at a circle in the specified sequence. Measured accuracy would be limited primarily by tracker noise or by variability within the saccadic system (Kowler & Blaser, 1995), not by the efficiency of selection, since no selection was required. Each saccade was classified using the nearest neighbor criterion above. The results show that the vast majority of saccades (98% for EV; 95% for KM; 90% for MJB; 90% for VK and 95% for BS) were classified as following the prescribed path.

2.8 Statistical test

A repeated measures ANOVA was used to test the statistical reliability of the effects of circle width and trial duration on saccadic performance. The ANOVA was based on the average performance from each subject. Each subject's average performance was based on the average on each trial. The trial average was used given that the saccades within the same trial may not be independent of each other (Wu et al., 2010). In the ANOVAs, subjects are treated as a random effect variable and the other factors are fixed effect variables (Myers, 1979).

The results presented below in each graph are the average performance from each subject, where a subject's average performance was based on the average on each trial. Overall, the results were also consistent with the results from individual subject's data.

3. Results

3.1 Psychophysical performance in the statistical estimation task

Before reporting the properties of the eye movements, performance in the statistical estimation task will be examined to verify that the estimation of the population mean improved, as expected, as the number of target circles fixated increased. This is necessary in order to show that the task provided incentive to continually search for targets. The performance is also compared to that of an ideal observer whose performance was limited only by the number of targets sampled and by the variability of the information in the samples.

The performance of the ideal observer on a given "trial" was calculated by drawing *N* samples (*N* = 1-6) from a Gaussian distribution whose mean was randomly chosen from the 4 population means (+/-30 or +/-10, *SD* = 20). The response of the ideal observer was set to the value of the population mean that was closest to the mean of the samples. This process was repeated 10,000 times for each value of *N*. *Figure 5* shows that both the ideal observer and the subjects improved in similar ways as the number of fixated target circles increased. The result of ideal observer indicates that, to improve the performance, it is necessary to keep looking for target circles, rather than merely using one or two samples to make the estimation. The improved performance with the numbers of targets fixated suggests that subjects were motivated to continue searching for targets, as expected. The performance of both ideal observer and subjects reached an asymptote after about 3-4 targets, although the subjects' estimation underperformed ideal observer by about 10-15 %.

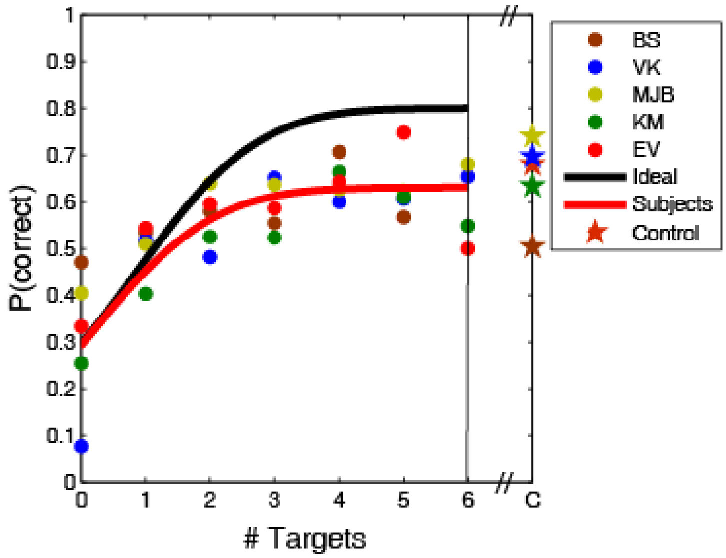


Figure 5. Proportion of correct estimation as a function of the number of target circles fixated for human observers (red line) and ideal observer (black line). Color code represents different subjects' performance. Each datum point is based on at least 30 trials. The star signs on the right axis represent subjects' average estimation performance in the control experiment, where all six tilted lines were shown at once around initial fixation.

This underperformance could have been due to decay of memory for information seen early in the trial (Epelboim & Suppes, 2001; Kibbe & Kowler, 2011). In order to evaluate this possibility, a control experiment was run in which all six sample oriented lines were provided simultaneously around central fixation without any distractor circle. This condition minimized memory decay since there was no need to spend time on serial visual search. Even when all samples were provided at once, performance did not change appreciably and still fell below the ideal observer (*Figure 5*, star signs on the right-hand axis). This suggests that memory decay during search did not account for subjects' underperformance. Subjects' underperformance may be due to the noise during encoding each target sample or inefficient integration of target samples during the decision process.

Performance in the statistical estimation task also depended on distractor width. *Figure 6* shows that the average performance improved as distractors became wider, and thus more discriminable from the thin target circles. The improvement was likely due to the increase in the numbers of targets fixated, as will be described below.

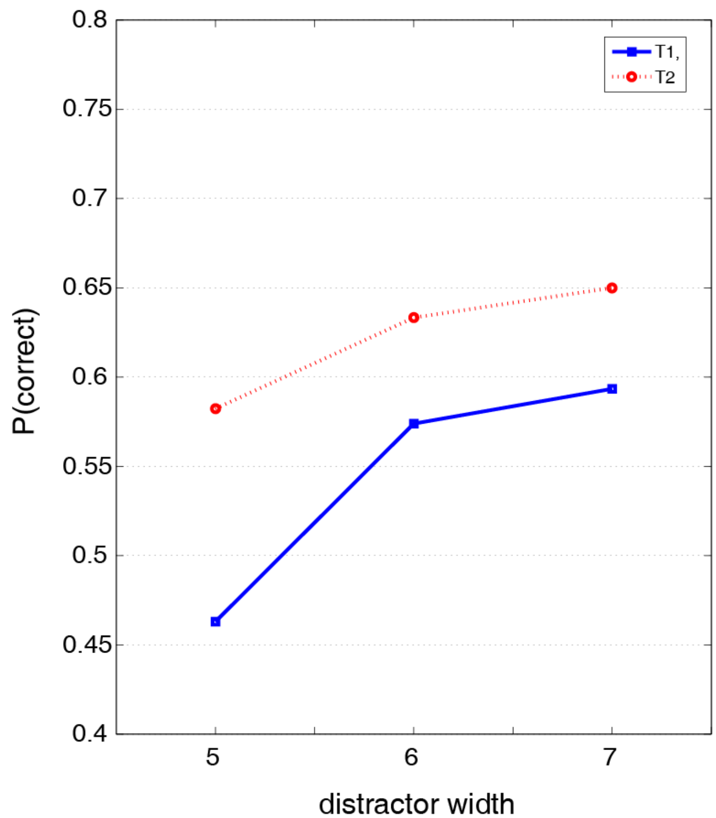


Figure 6. Performance of the statistical estimation task as a function of distractor circle width for 2 different stimulus durations. Blue line represents 1 second trial duration (T1) and red line represents 2 second trial duration (T2).

3.2 Selectivity of saccades improved with target/distractor discriminability

Evaluating the saccadic strategy requires examining two aspects of performance, the timing of saccades and the accuracy of fixating targets.

One way to evaluate the accuracy of finding targets is by examining the selectivity of saccades. *Saccadic selectivity* refers to the proportion of primary saccades landing closer to a target circle than to any distractor circle using the nearest neighbor criterion described above (section 2.7). To facilitate comparison across the 1s and 2s trial durations, all analyses were done based on the saccades occurring within each second. Therefore, for each circle width, performance will be shown for the three different 1-second long temporal epochs: (1) 1 s trials, (2) the first second of 2 s trials, and (3) the last second of 2 s trials. Selectivity was calculated as the number of primary saccades in each temporal epoch that landed closer to a target than to any distractor divided by the total number of primary saccades in that temporal epoch. Notice that any circle fixated by primary saccades was counted in this measure, regardless of whether the circle had been visited previously or not. Nevertheless, the same circle was barely fixated twice in the same temporal epoch. The overall revisit rate was less than 6% for 2 second trials and less than 2% for 1 second trials.

In addition, to evaluate whether saccadic selectivity had achieved the best performance, given the expected limits due to visual acuity (see Fig. 3b), performance is also shown for an ideal observer that is limited only by the ability to distinguish targets from distractors. This ability depends on eccentricity, as was shown in Fig. 3b. This simple model aims a simulated saccade to the nearest detected target, given the eccentricities of the different locations prior to each saccade. The model has no memory, other than for the targets fixated, in order to avoid revisits. This ideal observer makes errors when it falsely categories a distractor as a target (see Appendix A for the details).

Figure 7a shows that saccadic selectivity depended on the discriminability between targets and distractors. Saccadic selectivity increased from about 50% to 80% as discriminability increased over the range tested. Effects of circle width were significant in both the statistical estimation and the look-only tasks. Effects of temporal epoch were significant only in the estimation task (see Table 1).

To test the effect of task type, a paired t-test was conducted with each pair taken from the average performance for one subject in a given condition of the estimation and the look-only task (for each circle width and temporal epoch). The result showed that saccadic selectivity was about the same both in the estimation task and in the look-only tasks, even though achieving high selectivity was emphasized in the instructions of the look-only task ($t(44) = 0.57$, $p = 0.57$).

Figure 7 also shows the performance of the ideal observer that was limited only by visual acuity. The model out-performed subjects in the first second of trials, but was slightly poorer than subjects in the second part of the 2-s trials. When selectivity was analyzed over all saccades, regardless of temporal interval, selectivity of the model was better than the subjects' performance (*Figure 7b)*. This result implies that subjects did not adopt the same strategy as the model, in which saccades were always aimed to the closest target circle and there was no memory for target locations across fixations. The underperformance was not simply due to the limit of visual acuity, but to some other factors.

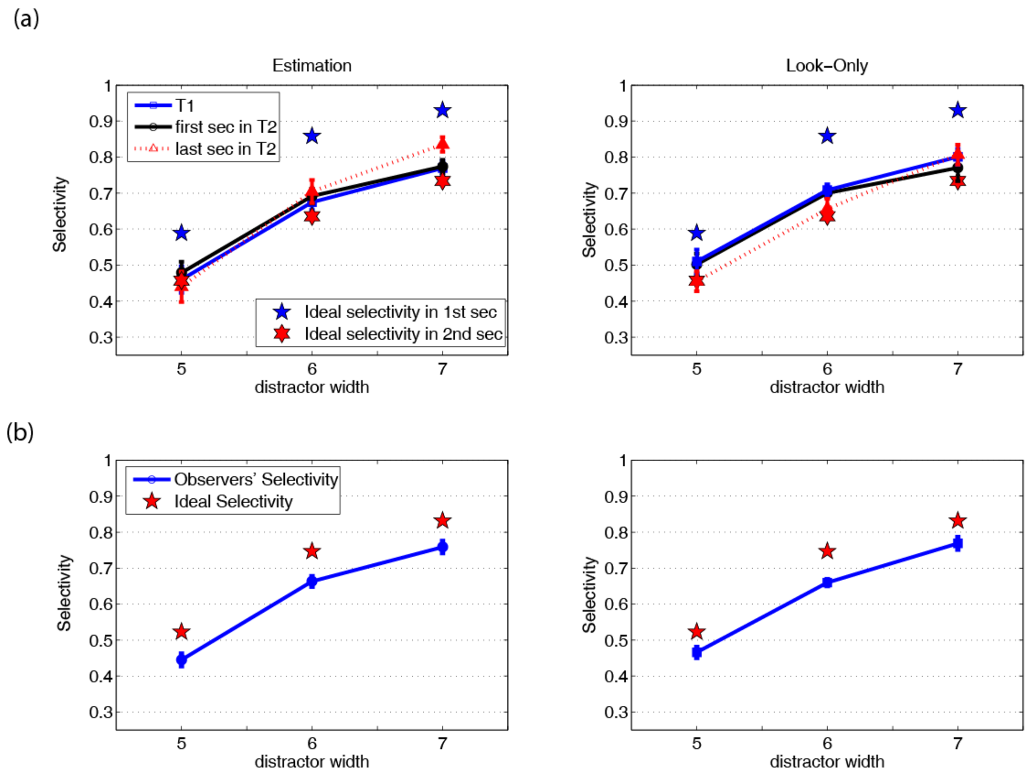


Figure 7. (a) Saccadic selectivity as a function of distractor circle width in the statistical estimation task (left) and the look-only task (right). (b) Saccadic selectivity for subjects' average performance during entire search sequences (duration = 2 sec). The star signs represent the best performance subjects could make predicted by their visual acuity (*Figure 3*b, also see appendix A). Selectivity was defined as the ratio of the number of target circles fixated divided by the number of total circles fixated during a trial. Three different lines represent 3 temporal epochs (blue: 1 s trial; black: first second of the 2 s trial; red: last second of the 2 s trial). Bars show ± SE; otherwise, SE's are smaller than the plotting symbols. Notice that subjects' and model's results were plotted as the summary of average performance from each subject.

Summary so far:

The accuracy of psychophysical performance in the tilted line judgment (Fig. 5), and the accuracy of selecting targets (Fig. 7), both show that subjects were doing about as well as could be expected given inevitable limits due to visual acuity. Although they underperformed plausible ideal observers in both cases, the amount of underperformance was not large. The good performance now sets the stage for the examination of saccadic timing.

3.3 Saccadic scanning rate

Prior studies found that saccades did not make full use of cues indicating target location (Hooge & Erkelens, 1999; Araujo et al., 2001). This implies that saccades may be initiated according to elapsed time, before enough information is acquired to determine target location. To evaluate this possibility, saccade rates were compared across the different difficulties of target selection.

Figure 8 shows saccade rates, the number of circles (target or distractor) fixated per second (the average performance from each subject). This measure includes any circle that may have been revisited during a trial (revisit rates were low; see section 3.2). Saccade rates reached higher values in the look-only task than in the estimation task, with rates approaching 3.3 saccades/s. Saccade rates increased slightly with circle width, but this was significant only in the look-only task. Saccade rates were also affected significantly by temporal epochs in both tasks. The detail of repeated measures ANOVA is shown in Table 2. In addition, a paired t-test also shows that saccade rates in the look-only task was higher than in the estimation task ($t(44) = 3.75$, $p < .05$).

Overall, increasing the width of distractors not only increased the ability of saccades to select the target (*Figure 7*), but led to faster rates of saccades as well. Appendix B shows results similar to *Figure 8,* plotted as dwell times between primary saccades.

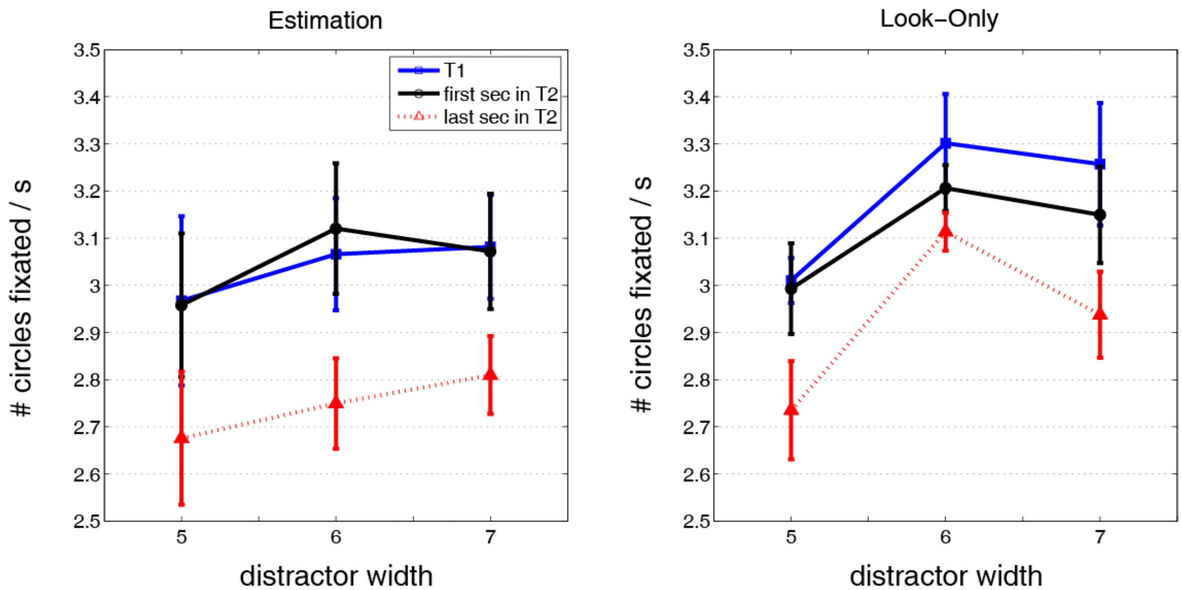


Figure 8. The number of circles fixated as a function of distractor circle width in the statistical estimation task (left figure) and the look-only task (right figure). Three different lines represent 3 temporal epochs (blue: 1 s trial; black: first second of the 2 s trial; red: last second of the 2 s trial). Bars show ± SE; otherwise, SE's are smaller than the plotting symbols.

Figure 9 shows the number of target circles fixated per second. This analysis incorporates the scanning rates (*Figure 8*) and the selection accuracy (*Figure 7*) and represents the net yield during the search sequences.

Figure 9 shows that the number of targets fixated increased with distractor width in ways that were quite similar to the improvements in selectivity. Effects of circle width were significant in both tasks. Effects of temporal epoch were significant only in the look-only task (See Table 3).

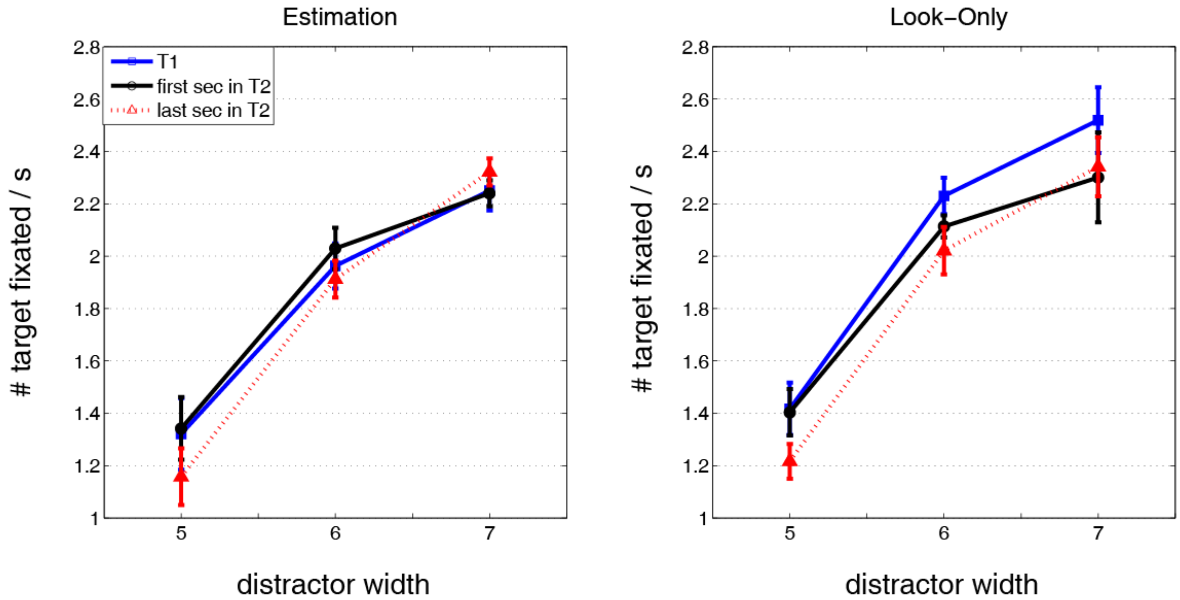


Figure 9. The numbers of target circles fixated as a function of distractor circle width in the statistical estimation task (left figure) and the look-only task (right figure). Three different lines represent 3 temporal epochs (blue: 1 s trial; black: first second of the 2 s trial; red: last second of the 2 s trial). Bars show ± SE; otherwise, SE's are smaller than the plotting symbols.

Given the higher saccade rates in the look-only task (*Figure 8*), the number of targets fixated per second in the look-only task (*Figure 9*) was higher than in the estimation task even though selectivity was about the same in both tasks (*Figure 7*).

Summary so far:

Figure 8 and Figure 9 show that scanning rates were limited by the task. When the cognitive load was reduced (look-only), higher rates of saccades were achieved. In addition, in the look-only task, subjects did not adopt a strategy of a relatively constant scanning rate, regardless of selection difficulty. In the look-only task, in which the cognitive load was reduced, subjects waited longer to acquire more information when selection difficulty increased. Saccade rates were lower and affected less by difficulty in the estimation task.

3.4 Dwell time was modulated based on the currently fixated content.

The results above show that saccade rates were faster when the cognitive load was reduced in the look-only condition. This implies that the saccadic timing strategy may be affected by the currently fixated content. That is, if timing depends on the currently fixated content, the line of sight may dwell longer on targets than on distractors. In addition, it is possible that taking the nature of the fixated content into account may also affect the conclusion about effects of difficulty on timing (*Figure 8*, *Figure 9*).

Primary saccades were sorted into four groups according to the type of circle that was currently fixated (target or distractor) and the type of circle that the saccade landed on (target or distractor). This analysis only included the saccades in the longer trials (2s) in order to obtain sufficient numbers of samples in each of the four groups. In addition, the first saccade of the search sequence was also excluded since it left from the initial fixation instead of from a specific circle.

Figure 10 shows the results plotted as dwell time, where dwell time is defined as the pause time between two consecutive primary saccades (see example in *Figure 4*), minus the in-flight time of any secondary saccades (Wu et al., 2010). *Figure 10* shows that dwell time depended more on where the line of sight was currently looking than where it was going to land (blue and black lines correspond to the left axis). The repeated measure ANOVA also indicated that dwell time was affected significantly by the circle (target or distractor) currently fixated (Table 4). Dwells were much longer (50-100 ms) when saccades were leaving from a target than leaving from a distractor in either the statistical estimation or the look-only tasks. Table 5 also shows this applies to individual subject's data. The longer dwell times on targets in both tasks implies that time was not just spent on evaluating the tilt of the line, but other processes because saccades on target circles still had longer dwells even in the look-only task where there was no need to estimate the tilt of the line.

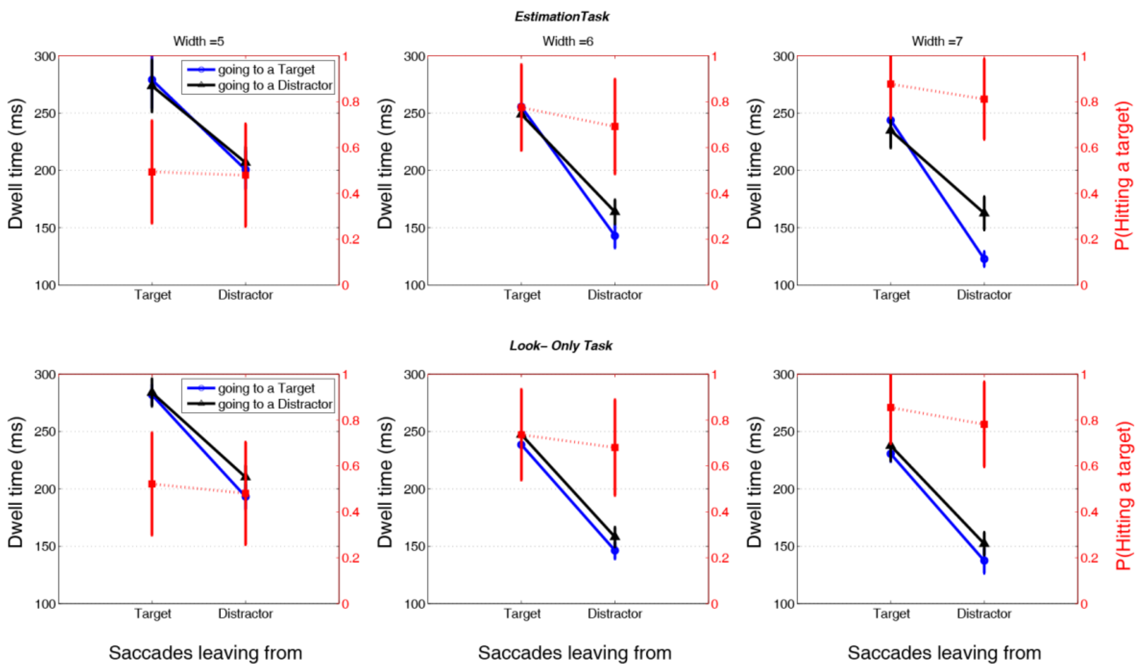


Figure 10. . Dwell time as a function of saccade starting locations and landing positions (target/distractor) in the estimation task (top row) and in the look-only task (bottom row). Data were only for longer trial duration (2 second). Blue lines represent the dwells of saccades going to a target and black lines represent the dwells of saccades going to a distractor. The superimposed red lines represent the probability of hitting a target as a function of saccade starting locations (red axis on the right hand side). Bars show ± SE; otherwise, SE's are smaller than the plotting symbols. Notice that the first saccade in the sequence was not include because the first saccade left from initial fixation instead of any type of circles.

Figure 10 also shows effects of selection difficulty (circle width) on timing. For both tasks, dwell times decreased as selection difficulty decreased. This was true for saccades leaving from targets or from distractors. The decrease in dwell time over the range of difficulties was about 30-50 ms. Thus, the lack of an effect of task difficulty on timing in *Figure 8* applied only to overall rates, but not when the performance was broken down according to the currently fixated location.

One unexpected result in *Figure 10* is shown by the difference between the functions in each graph. Specifically, saccades going to targets (blue) usually had slightly shorter dwell times than saccades going to distractors (black), even though these effects of saccadic landing position was only significant in the look-only task (Table 4). This is opposite to the expectation that saccades landing on distractors did so because planning time was too short. Nevertheless, this result is consistent with a timing strategy that is actively seeking targets. For example, if no nearby or highly visible targets were readily available, the saccade maybe delayed slightly in an attempt to decide on an appropriate landing site. Delays might not be as long for saccades leaving from targets (the data points on the left of each graph) because the dwell times may have been already long enough to include enough time to choose the landing site.

Interestingly, the longer dwell times on targets were also associated with an increased probability of landing on a target on the next saccade, as shown by the (slightly) higher levels of selectivity achieved when looking currently at a target (*Figure 10*, red line, right y-axis). That is, saccades leaving from targets were more likely to land on a target than saccades leaving from distractors. This result, comparable to Hooge and Erkelens (1999), suggests that longer dwell times, due to the need to evaluate the fixated information, may also improve the accuracy of target selection.

In summary, *Figure 10* shows that saccadic timing depended on both selection difficulty and on the type of currently fixated target in both tasks. In addition, when dwell times were short, and a target may not have been discovered, subjects delayed saccades a short time longer perhaps as part of the attempt to use visual information to find a suitable landing location.

3.5 Saccadic planning over the course of a trial

One of the results in *Figure 10* was that saccades going to a distractor had slightly longer dwells than saccades going to a target. This result implies that if there is no available target nearby, subjects would wait a little bit longer, then made a saccade to a region where they might be more likely to find a target. This may indicate that subjects look for a target at a close eccentricity during search. To further demonstrate whether subjects preferred nearby targets, the eccentricity of the fixated target, when saccades went to targets, was compared to the eccentricity of the nearest available target, when saccades went to distractors.

Figure 11 shows the eccentricity of the target fixated (blue line), or the eccentricity of the nearest available target (red line) when subjects fixated a distractor, as a function of the ordinal position of primary saccades (the small proportion of revisits were included). The result shows that eccentricity was smaller for the fixated targets (blue) than for missed targets (red). This supports the view that saccades preferred to go to nearby targets. *Figure 11* also shows that the eccentricity of targets increased with ordinal position both for saccades going to a target and saccades going to a distractor. This also implies that subjects preferred fixating nearby targets first. The repeated measure ANOVA confirms that the effects of landing positions and saccadic ordinal position were significant (**Table 6**).

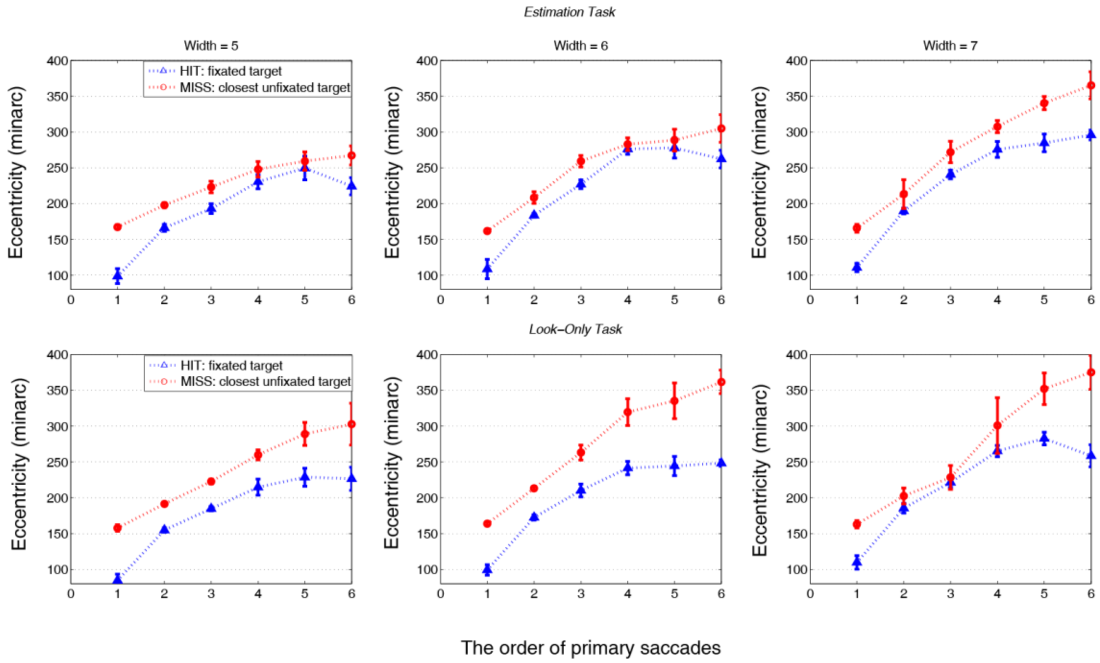


Figure 11. Eccentricity of target circles as a function of the ordinal position of primary saccades for three levels of selection difficulty in the estimation task (top) and the look-only task (bottom). Blue lines represent saccades going to a target (HIT) and red lines represent saccades going to a distractor (MISS). Bars show ± SE; otherwise, SE's are smaller than the plotting symbols.

The result in *Figure 11* suggests that subjects preferred targets at a close eccentricity. When the eccentricity was too large, subjects may fixate a distractor rather than fixate a target. In addition, this result also implies that the difficulty of target selection may increase over time due to the increase in target eccentricity. How can this pattern be related to saccadic timing? Above we saw that scanned slower when target selection became harder (*Figure 8* & *Figure 10*). Did subjects also scan slower as the sequence proceeded, when target selection became harder due to an increase in target eccentricity? To answer this question, saccadic dwell time was analyzed as a function of the saccadic ordinal position. This was done separately for saccades to targets (Hit) and to distractors (Miss), as was done in *Figure 11*.

Figure 12 shows two main results: First, dwell time was affected by the saccadic ordinal position, but in a different way as target eccentricity in *Figure 11*. Dwell times were short at the beginning, increased during the middle of the sequence, then slightly decreased at the end of the sequence. The results were similar in the estimation task and the look-only task. Second, dwell times before saccades to targets were about the same as dwells before saccades to distractors. The exception, however, was the first two saccades in the search sequence when target selection was easy (width = 6 or 7), where saccades going to a target had longer dwells. This tells us about saccadic timing strategies: For the easier levels of selection difficulty (width 6 or 7), subjects delayed saccades to improve the accuracy of target selection initially, but not in subsequent saccades. These delays at the beginning of the sequence were associated with shorter dwells. The repeated measure ANOVA confirmed that the ordinal position, but not the type of circles about to be fixated, had significant effects on the timing of saccades (**Table 7**). As would be expected from examining *Figure 12*, the interactions between ordinal position and selection accuracy (hit vs. miss) and ordinal position and selection difficulty (width) were both significant.

In summary, *Figure 11* and *Figure 12* show effects of ordinal position on saccadic timing. There was some evidence for improved selection accuracy with longer pause durations early in the sequence. Later, however, saccades did not pause long enough to aim for the best performance during search since saccadic dwells were similar between saccades going to a target and saccades going to a distractor.

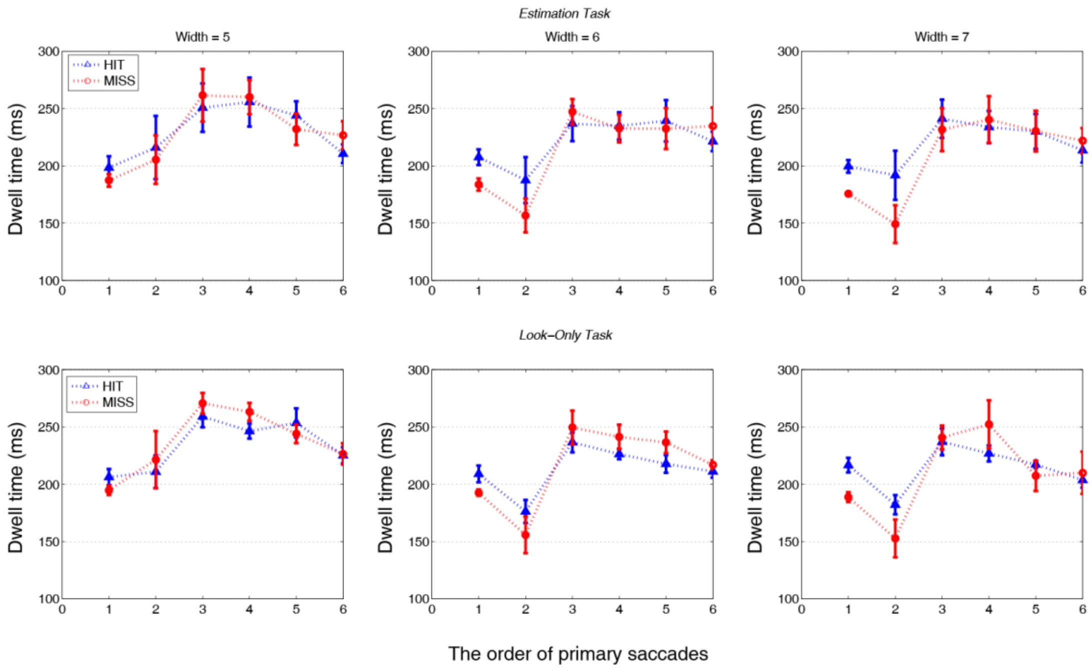


Figure 12. Saccadic dwell time as a function of the ordinal position of primary saccades for three levels of selection difficulty in the estimation task (top) and the look-only task (bottom). Blue lines represent saccades going to a target (HIT) and red lines represent saccades going to a distractor (MISS). Bars show ± SE; otherwise, SE's are smaller than the plotting symbols.

One more analysis of effects of ordinal position was carried out. Notice that *Figure 10* has shown that saccades going to distractor had longer dwells than saccades going to a target when the currently fixated location was taken into account. To determine how the effect of currently fixated location may have applied to the data shown in *Figure 12* (effects of ordinal position), *Figure 12* was further analyzed according to the type of circle that was currently fixated (target or distractor). The first saccade in the sequence was not included because the first saccade did not leave from a specific circle.

Figure 13 shows that, for saccades leaving from a target, saccades going to a target had similar dwells as saccades going to a distractor. When saccade left from a distractor (*Figure 13*, bottom), however, saccades going to a distractor had longer dwell than saccades going to a target especially when target selection was easy. Notice that this counterintuitive result happened only in a few cases because subjects rarely selected two distractors in a row when target selection was easy. Therefore, this large difference between Hit and Miss cases is only barely apparent when data are collapsed across the currently fixated location, as was done in *Figure 12*.

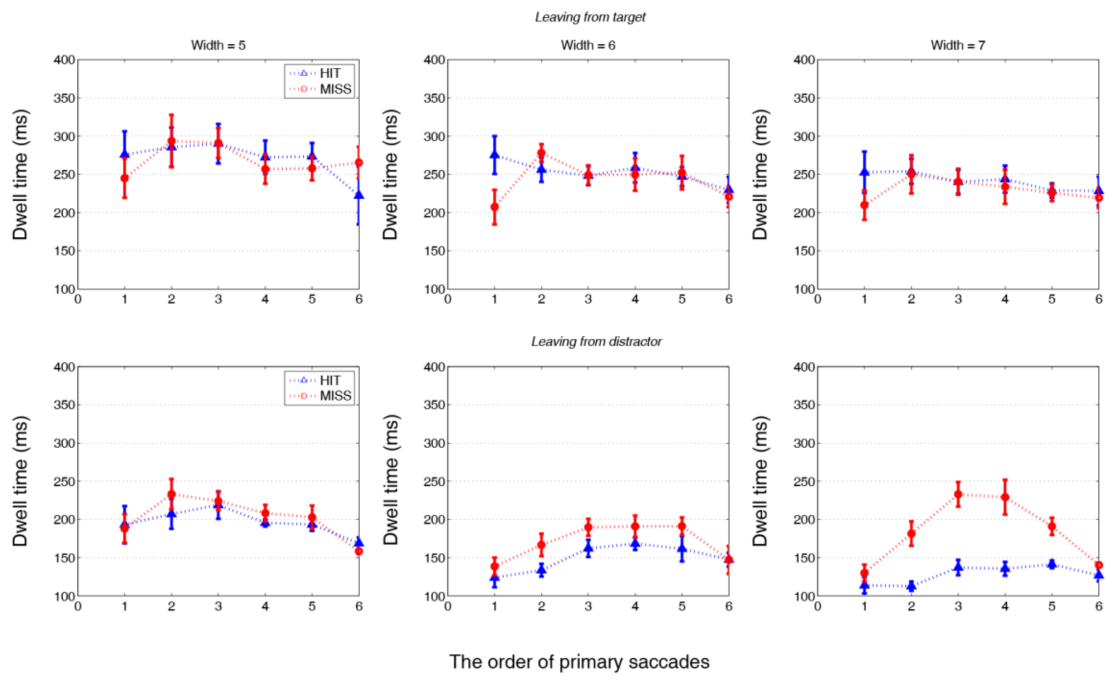


*Figure 13***.** Saccadic dwell time as a function of the ordinal position of primary saccades for three levels of selection difficulty for saccades leaving from a target (top) and saccades leaving from a distractor (bottom) in the estimation task. Blue lines represent saccades going to a target (HIT) and red lines represent saccades going to a distractor (MISS). Bars show ± SE; otherwise, SE's are smaller than the plotting symbols.

3.6 Scanning strategy: subjects vs. ideal observer

Figure 14 shows that subjects' saccades size and saccadic selection accuracy were very similar to the "nearest target" strategy used by the ideal observer model that was presented earlier (*Figure 7*). Any revisited saccade would not be included in this analysis.

The big difference was the first two saccades in the sequence (short dwells, *Figure 12*) where the model did much better than subjects. The trend reversed after the third saccade for the easy selection. Thus, saccades may be planned too fast in the beginning and the accuracy of selection was scarified for faster scanning rates. After that, saccade rates became slower and saccadic landing accuracy was improved. Notice that the trend of saccadic selection accuracy was quite different between the model and subjects. Model performance became worse over time. Subjects' selection accuracy was better than the model's in the later of the sequence when target selection was easier.

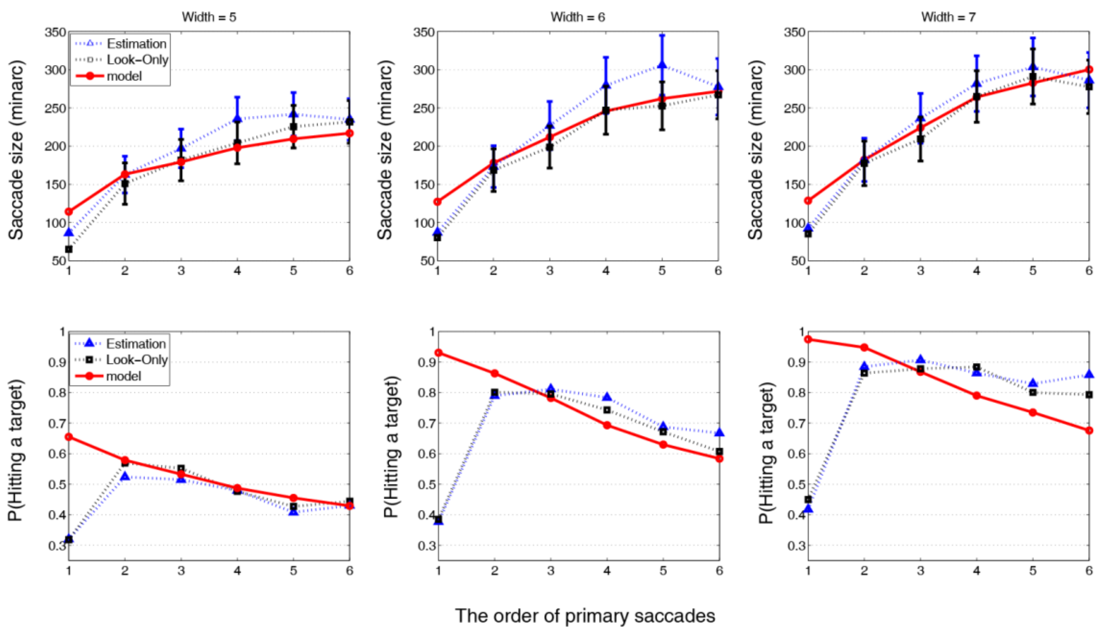


Figure 14. Saccade size (top) and selection accuracy (bottom) as a function of the ordinal position of primary saccades for three levels of selection difficulty. Red lines represent the performance of model which was based only on the visual acuity. Blues lines represent subjects' performance in the estimation task and black lines represent performance in the look-only task.

3.7 Increase pause duration by lowering contrast

The results above showed that saccades made to targets had similar dwells as saccades made to distractors (*Figure 12*). This suggests that, given a level of selection difficulty, subjects did not always prolong saccadic planning time to improve the accuracy of selection. The decision of when to initiate next saccade doesn't seems to depend only on accumulated target information, but rather it may emphasize *consistent timing*, since the dwells were about the same for saccades going to a target and saccades going to a distractor (*Figure 12*). Nevertheless, dwell time was longer when saccades were leaving from a target than when saccades were leaving from a distractor, and these longer dwells resulted in a slightly higher probability of landing on a target for the next saccade (*Figure 10*, red lines).

A strategy of consistent timing may be due to several factors: (1) Saccade selectivity may have reached its best level and longer pauses would not improve target selection. Therefore, instead of prolonging the pause, the system adopts the highest useful saccade production rates to increase the frequency of fixating more target circles. (2) Consistent timing may be a default strategy during visual search, and people would keep an efficient saccade rate, even though longer pauses might improve the accuracy of target selection.

In order to evaluate these possibilities, a comparable experiment was run in which the difficulty of evaluating currently fixated content was manipulated by varying the contrast of the lines inside the target circles. In this way, subjects would pause longer due to the lower contrast of the lines. Hooge and Erkelens (1999) suggested that increasing pause duration by increasing the difficulty of the foveal task would improve the ability to find and fixate targets in search. This new experiment addressed the question of whether longer pauses can further improve the accuracy of target selection during the statistical estimation task and see how the timing strategy changes with the difficulty of foveal analysis.

3.7.1 Methods

Six subjects were run in the same statistical estimation task, including three tested previously and three new subjects. Only the longer trial duration (2 second) was tested. The stimulus display and experimental procedures were the same as above except the contrast of visual element inside each circle (either one single dot or a tilted line) was set to one of three different levels (low, medium or high contrast, where the luminance of each was 101, 51 and 19 cd/m^2, respectively). The background luminance was the same as Experiment 1 (white background, luminance = 168 cd/m^2).

3.7.2 Results of decreasing contrast

Figure 15 shows that when stimulus contrast decreased, saccadic dwell time increased accordingly. For each stimulus contrast, saccadic dwell time slightly increased when the target selection became harder. The repeated measure ANOVA also shows that there was a significant effect of stimulus contrast on saccadic dwell time (**Table 8**).

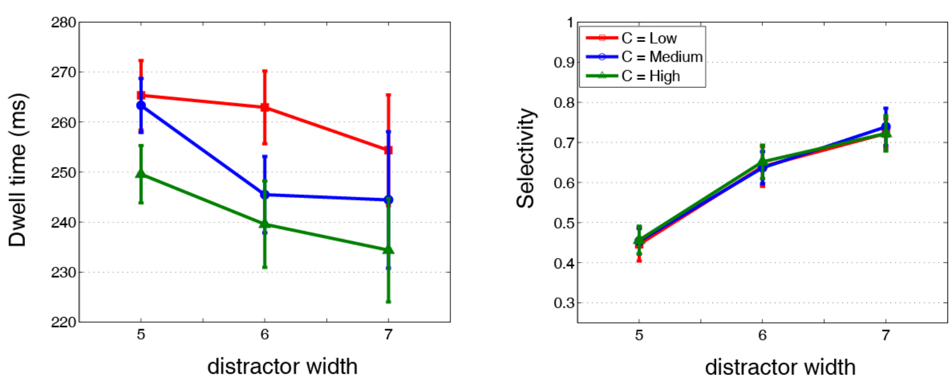


Figure 15. Left: Saccadic dwell times as a function of distractor width for three levels of stimulus contrast (low, medium and high contrast). Right: Saccade selectivity as a function of distractor width for the three levels of stimulus contrast. Bars show ± SE; otherwise, SE's are smaller than the plotting symbols.

When dwell time increased due to the lower stimulus contrast, the accuracy of target selection remained the same across the different levels of distractor widths (*Figure 15*, right). That is, saccadic selectivity was affected only by the difficulty of target selection due to the smaller circle width, and was not improved by the longer pause duration. A repeated measure ANOVA also confirms this result (**Table 9**). This result shows that the control of saccadic timing was mainly affected by the fixated content, not by the selection difficulties.

When saccades were divided based on the type of circle subjects currently fixated and the type of circle saccades were going to land (*Figure 16*), similar results were found as in *Figure 10*. For each level of stimulus contrast, saccades leaving from a target had longer dwells than saccades leaving from a distractor. Saccades going to a target did not have longer dwells than saccades going to a distractor. The increase in dwells due to the need to evaluate fixated content still resulted in a better accuracy of target selection (*Figure 16*, red line). The increase in dwells due to the lower visual contrast, however, did not affect selection accuracy.

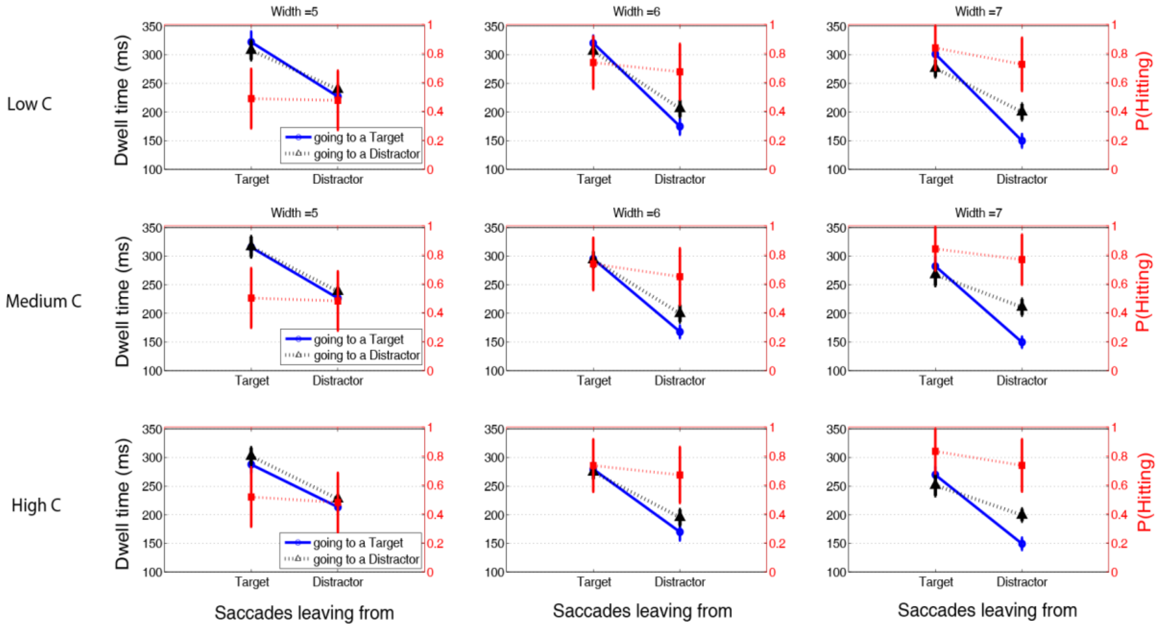


Figure 16. Dwell times as a function of saccade starting locations and landing locations (target/distractor). Each row represents one level of stimulus contrast (low, medium or high contrast). Blue lines represent the dwells of saccades going to a target, and black lines represent the dwells of saccades going to a distractor. The superimposed red lines represent the probability of hitting a target as a function of saccade starting locations (red axis on the right hand side). Bars show ± SE; otherwise, SE's are smaller than the plotting symbols. Notice that the first saccade in the sequence was not include because the first saccade left from initial fixation instead of any type of circles

In addition, similar to *Figure 10*, dwell time was not only affected by the type of circle currently fixated, but also by the type of circle saccades were going to land on. When target selection was easy (width = 7), saccades leaving from a distractor had longer dwells for saccades going to a distractor than saccades going to a target (*Figure 16*). In general, saccadic dwell times were affected significantly by the type of circle currently fixated, the type of circle going to be fixated, stimulus contrast and circle width (see **Table 10** for ANOVA).

Summary:

The results show that during visual search subjects adjusted saccade pause duration based mainly on the visibility of the immediate fixated content. The accuracy of target selection did not benefit from longer pause durations. But the increase in dwell time due to the lower contrast was only about 30 ms (*Figure 15*), which may be too small to improve selection accuracy. By contrast, the increase in dwell time due to the nature of the currently fixated location (target or distractor) was about 100 ms (*Figure 16*, both blue and black lines), which may be sufficient to improve the accuracy of target selection. This implies that the rates of scanning shown in Fig. 8- Fig. 13 could already be an efficient rather than a reckless strategy. The underused information from peripheral vision, which was concurrently processed during foveal analysis, may be sufficient to guide saccades, and little would be gained by further delays.

4. Summary

The main question in the current study is what determines the timing of saccades in a search task with multiple targets. The results show that the timing patterns of saccades depended on several factors:

1. Similarity of targets and distractors: As targets and distractors became more distinguishable from one another, the proportion of saccades landing near targets increased (*Figure 7*), and saccade rates (saccades/second) increased (*Figure 8*). The effect of the difficulty of target selection became apparent when saccades were examined separately as a function of the currently fixated location (*Figure 10*).

2. Task requirements: The maximum rate of scanning was higher in the look-only task than the estimation task (*Figure 8*). Differences in scanning rates between the tasks were evident when target and distractors were easily discriminable and saccade rates reached their highest levels (width 6 and 7). This shows that the requirements of the estimation task did add to dwell times, suggesting an overlap between the foveal requirements of the task and the processes contributing to target selection.

3. The currently fixated content: Dwell times were longer when looking at targets than when looking at distractors. Similar results were also found in the

look-only tasks where there was need to analyze the line tilt in the target circles.

4. The nature of the target of the saccade: In some cases, dwell times prior to saccades that landed on or near targets were shorter than dwell times prior to saccades that landed on or near distractors (*Figure 10*). The effect of the nature of the saccadic target was most apparent under conditions where dwell time was already short (i.e., saccades leaving distractors in the easiest condition).

5. The ordinal position: For each difficulty of selection, dwells were longer in the middle of the sequence and shorter in the beginning and end of the sequence. Similar patterns were observed regardless of where saccades going to a target or a distractor.

5. General Discussion

The fundamental questions about saccadic planning have not changed over past two decades: How do people deploy gaze, and what determines decisions about where to look next? Most prior studies focused on the spatial element of saccadic decisions. That is, where do people look during different viewing tasks? Several theories were proposed to explain how people deploy their fixations, such as bottom-up control governed by a salience map (Koch & Ullman, 1985, Itti & Koch, 2001; Zehetleitner, Hegenloh, & Müller, 2011), or top-down control governed by viewing of task-relevant elements (Droll, Gigone & Hayhoe, 2007; Jovancevic-Misic & Hayhoe, 2009; Rothkopf, Ballard and Hayhoe, 2007) or semantically relevant items (Hwang, Wang & Pomplun, 2011). Other theories emphasized maximizing information gain by adopting a Bayesian searcher (Najemnik & Geisler, 2005, 2008, 2009). Nevertheless, most of these studies did not take the temporal element into account. Saccadic decisions cannot be well understood without considering this limited resource, namely, time.

A key issue motivating the present study is to understand the strategies behind the control of saccadic timing, and how saccadic timing may be modulated in ways that would increase the likelihood of finding targets. In order to find as many targets as possible, there may be two different strategies people could adopt.

First, people could use a high scanning rate to increase the frequency of fixations, regardless of the difficulty of selection. This implies that there is an internal timer used to maintain a high rate of fixations, regardless of the accuracy or utility of target selection. A high rate of fixations would lead to more targets fixated during tasks such as visual search. If people used this strategy, saccadic selectivity will depend mainly on the difficulty of finding targets. Scanning rates should be similar across different levels of difficulty since there would be no extra time devoted to planning saccades when selection becomes harder. This strategy is supported by previous studies (Hooge & Erkelens, 1999; Araujo et al., 2001), which suggested that modulating timing to achieve better selection was not the preferred strategy of saccadic planning.

An alternative to maximizing the scanning rate across different conditions is to spend as much time as needed during each fixation pause until the evidence about target location is sufficient. In this case, people would pause longer and scan slower to improve saccadic selectivity. This implies that saccadic decisions are based on the evidence about target location. During each fixation pause, information about target location would be accumulated over time in eccentric vision, and a saccade would be triggered when the accumulated information reached an internal criterion. Many studies had found results consistent with this idea. For example, Carpenter, Reddi & Anderson (2009) found that saccadic reaction time to the appearance of an eccentric target can be predicted by how fast the system accumulated evidence about the target. In the present experiment, if saccades were initiated only when people accumulated enough evidence, saccadic selectivity should be close to the best performance subjects could achieve, limited only by visual acuity, and saccade scanning rate should depend on the difficulty of selection.

The results obtained supported neither of these two extremes. Contrary to the first alternative, the timer, subjects did not scan at a uniform rate. Subjects scanned slower when target selection became harder (*Figure 8 & Figure 10*). On the other hand, contrary to the second alternative, saccadic selectivity depended on the difficulty of selection and underperformed the best possible performance predicted by their visual acuity, particularly early in the sequence (*Figure 7 & Figure 14)*. This means that the criterion for initiating a saccade was not solely based on discovering a target, but on some other signals.

The preliminary psychophysical results (*Figure 3b*) showed that, given sufficient pause duration, subjects' ability to distinguish the difference between targets and non-targets changes as a function of target eccentricity. These results can be used to predict selection accuracy during the search sequence (*Figure 14*). If saccades were made only when a target was located, saccade selectivity should be similar to the performance predicted by visual acuity. Since subjects did not achieve the best selection accuracy, especially early in the sequence, there must have been a strategy of sacrificing at least some level of the selection accuracy to maintain a high level of scanning.

Overall, the results show that saccades were not made with the highest possible production rate regardless of the accuracy of selection, nor did saccades aim for the best possible selection accuracy, regardless of how much time was needed to find the target. That is, the timing of saccadic planning was not solely depended on either a fixed internal timer or an evidence accumulator. The results instead suggest that decision of when to initiate a new saccade took into account several sources of information, including information processed from the current fixated content, accumulated information from eccentric vision for better target selection, and possibly, a deadline for launching a saccade if a target was not found. These three influences on timing will be discussed below.

1. *The timing of saccades depended on the currently fixated content*

Hooge and Erkelens (1999) found that the control of fixation duration depended mainly on the difficulty of the foveal discrimination task. Although they did not find that increasing the difficulty of selection had an effect on saccadic pause duration, they found longer duration due to the higher difficulty of analyzing current fixated content did result in a better target selection. In the present task, saccades paused longer when the difficulty of analyzing fixated content became harder due to the lower stimulus contrast (Exp 2). Moreover, saccades leaving from a target had much longer dwells than saccades leaving from a distractor (*Figure 10* & *Figure 16*). These longer dwells, in agreement with Hooge and Erkelens (1999), also led to better selection accuracy.

One unexpected result was that saccades had longer dwells when leaving from a target even in the look-only task, where there was no need to evaluate the angle of the tilted line. Why did saccades pause longer when leaving a target than when leaving a distractor? The difference in dwell time may be due to two factors: (1) The longer dwells may be needed to conform that a target circle was being fixated. Each target circle always contained a tilted line, but each distractor circle only contained a single dot. The slightly higher visual complexity in target circles may also result in a higher dwell times. (2) The shorter dwell time when saccades were leaving from a distractor may be due to the search strategy. That is, the distractor circle may serve as an intermediate landing position when the target location was far away from the current fixation. In this case, the location of target was found, but it cannot be reached merely by using one single saccade. Therefore, subjects would use multiple saccades, landing briefly on the intermediate distractor to reduce the target eccentricity, and then using a follow-up saccade to reach the target (Coeffe & O'Regan, 1987). As a result, saccades landing on an intermediate distractor circle would only have a short pause since the target location was known even before saccades landed on the distractor circle. *Figure 10* also showed that dwells of saccades leaving from a distractor decreased as target selection became easier. This may be due to the fact that subjects were more likely to adopt the intermediate landing strategy as mentioned above when target selection was easier than when target selection was harder.

2. *Saccadic timing was affected by accumulated evidence in eccentric vision*

Instead of using consistent timing across different levels of selection difficulty, as found by Hooge & Erkelens (1999), the results of current study showed that subjects waited longer and scanned more slowly when target selection became harder. That is, when the discrimination in eccentric vision was harder, subjects paused longer in attempt to accumulate more information for better selection accuracy. This is supported by the results of *Figure 8* and *Figure 10*.

Figure 8 showed that subjects scanned more slowly when target selection became harder. When saccadic performance was examined by the type of circle currently fixated and the type of circle be looked at next (*Figure 10*), saccadic dwell time was significantly longer when selection was hard than when selection was easy.

Even though the timing of saccades was affected by accumulated evidence from eccentric vision, it does not mean saccades were triggered by the accumulated evidence. *Figure 7* has shown that subjects' saccadic selectivity underperformed the best possible performance predicted by the ideal observer based only on visual acuity. This implies that although pauses were longer to acquire more information when selection became hard, pause duration was not long enough for sufficient evidence to be accumulated.

3. The timing of saccades was controlled by an internal timer

As described above, saccades paused longer when target selection became harder. The underperformance of saccadic selectivity (*Figure 7*), however, suggests that subjects did not wait long enough to maximize the information gain from eccentric vision.

Another indication that a timer might be used was that saccades going to a target and saccades going to a distractor had similar dwell times (*Figure 12* & *Figure 13*). A similar result was also found in both tasks: saccades going a target and saccades going to a distractor still had similar dwell times even in the look-only condition. This suggests that a deadline, rather than information, was used to trigger saccades when there was no target found.

One exception to the above occurred when saccades were leaving from a distractor and the overall dwells were short (*Figure 10*, *Figure 13* & *Figure 16*, width = 6 or 7). Counterintuitively, in this case, saccades going to a distractor had longer dwell times than saccades going to a target in the easier conditions. It may be that when dwells was very short, the system paused longer to accumulate some additional information from eccentric vision. If a target was found during the accumulating process, a primary saccade would be launched to the target location immediately. If not, the system would keep waiting only up to a deadline was reached.

An alternative strategy - an adjustable timer

As described above, saccadic timing was affected by multiple factors, such as the currently fixated content, the accumulated evidence and an internal timer. What strategy could people use to incorporate all the factors and make the decision about when to look to a new location? One possibility is using a timer with an adjustable deadline.

The deadline of this timer may be modulated by the level of selection difficulty. That is, when target selection was harder, not only would the rates of accumulating target information became slower, but also system would set up a longer deadline to encourage longer pause durations. Therefore, when target selection was hard, saccades would scan slower and pause longer to accumulate more information. Once the deadline was reached, a new saccade would be initiated regardless of the accuracy of selection.

When target selection was easy, the system would set a shorter deadline and saccades may be triggered by evidence even before the deadline was reached once a nearby target was found. It is also possible that subjects retrieved information about target location from memory since there may be more than one target found at a time when selection was easy (Epelboim & Suppes, 2001). This alternative strategy is illustrated in *Figure 17*.

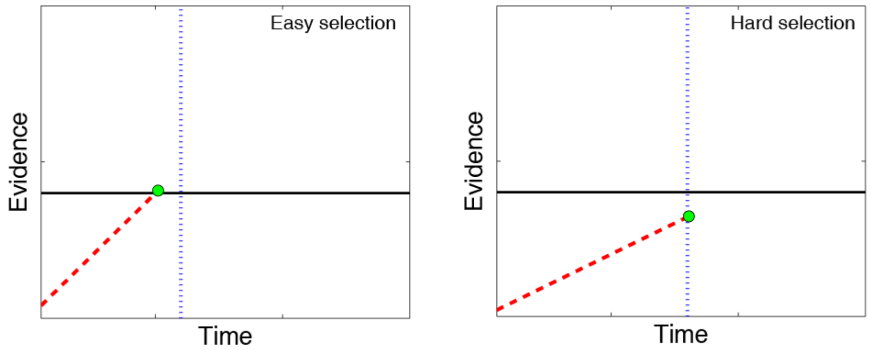


Figure 17. The hypothetic strategy subjects adopted in the search. The evidence about target was accumulated faster when target selection was easy than when target selection was hard. Saccades would be made either when criterion of evidence was reached (left), or when the internal timer was triggered (right).

This possible strategy may explain the results found in the current study. When the analysis of the currently fixated content was completed, the timer would decide whether a new saccade should be initiated right away (if it had passed the deadline), or it should pause longer and accumulate more evidence for better accuracy of target selection (if the deadline hadn't been reached). The deadline could be modulated based on the difficulty of target selection, the immediately fixated content, or even the task type. Using a timer to monitor how much time has been spent on the current fixation during visual search may guarantee the adequate use of visual information without overlooking it.

Other influences on the timing of saccades

In addition to factors, such as the difficulty of target selection or local information complexity, saccadic planning was also affected by higher level or global factors, which were not relevant to stimulus itself, such as the ordinal position of movement sequence.

Prior studies had found that timing of voluntary movements made in sequences varies with the ordinal position of the movement in the sequence, with patterns typically following an inverted-U shaped function, which had shorter reaction time in the beginning and in the end of sequence (Sternberg et al., 1978a,b; Zingale and Kowler, 1987). Such patterns are typically interpreted as evidence that individual movements are not planned one-by-one, but rather planned as a sequence. Similar results were also found in the present study. Dwell times varied as an inverted U shaped function (*Figure 12*). Those prior studies on the planning of sequential movements typically involved simple tasks, such as sequences of key presses, spoken syllables or saccades made to targets with known locations (Sternberg et al., 1978a,b; Zingale and Kowler, 1987). The present results show that saccades were planned as a patterned sequence even when target locations were uncertain. That is, saccadic planning was affected by subjects' expectation about the length of movement sequence and each saccade was not planned independently. Saccades to the next target may have been programmed even before saccades were reaching to the current fixation (McPeek, Skavenski, & Nakayama, 2000; Trukenbrod & Engbert, 2012).

Moreover, the decrease in dwell time near the end of the sequences may also show the effects of memory in the timing of saccades. That is, saccadic planning did not necessarily depend on the information accumulated during the pause prior to the saccade, but on the information recorded earlier in the sequence. When target selection was easy, subjects could detect multiple targets at a time and store target location information and use it for the subsequent saccades. This strategy could help maintain a high level of selection accuracy without being affected by the increasing target eccentricity over time.

The use of memory could also explain why subjects' selectivity was better than the model's in the end of search sequence when target selection was easy (*Figure 14*). This is due to the fact that model has no memory and would select a target only based on the information integrated during fixation pause. Our subjects, however, may find multiple targets at a time when target selection was easy. This information recorded in the beginning of the sequence would be used to plan the subsequent saccades and maintain a high level of selection accuracy without requiring much planning time. Therefore, subjects outperformed the model in the end of the sequence.

Conclusions:

The current work suggests that the decision of when to look next is not solely made by a timer with a fixed deadline, or by accumulated evidence. An adjustable timer seems to be used to make this decision. The way to set the deadline of the timer would consider the difficulty of target selection based on eccentric vision, the complexity of current fixated information and task types. By using this timer to make the saccadic decision, people may be able to apportion time adequately between processes of saccade production and saccade selection. These findings may help establish a model of timing in natural visual search and find out whether people can ideally apportion time and maximize information gain during visual search. One preliminary experiment is proposed to address this question (See Appendix C).

6. Tables

Table 1. The repeated measure ANOVA for saccadic selectivity in both tasks (Fig 7).[1]

	Selectivity in the estimation task					Selectivity in the Look-only task				
Source of Variance	***df***	***SS***	***EMS***	***F***	***p***	***df***	***SS***	***EMS***	***F***	***p***
Circle Width (W)	2	3.58	1.79	108.25	0.001*	2	3.23	1.62	64.78	<0.001*
Temporal Epoch (T)	2	0.12	0.06	18.11	0.0184*	2	0.01	0.01	0.52	0.61
Subjects (S)	4	0.39	0.10			4	0.28	0.07		
W*T	4	0.12	0.03	9.43	<0.001*	4	0.07	0.02	4.45	0.01*
W*S	8	0.13	0.02			8	0.20	0.02		
T*S	8	0.03	0.00			8	0.10	0.01		
W*T*S	16	0.05	0.00			16	0.07	0.00		
Total	44	4.42				44	3.96			

EMS: expected mean square

[1] [1] The reported statistics are based throughout on the angular transformation, $g(y) = 2\arcsin\sqrt{y} - (\pi)/2$, applied to the normalized smoothing measure (which ranges from 0 to 1) in order to improve the normality of its distribution (Hoaglin, Mosteller, & Tukey, 1991).

Table 2. The repeated measure ANOVA for scanning rates in both tasks (Fig 8)

	Scanning rates in the estimation task					Scanning rates in the Look-only task				
Source of Variance	***df***	***SS***	***EMS***	***F***	***p***	***df***	***SS***	***EMS***	***F***	***p***
Circle Width (W)	2	0.14	0.07	3.34	0.09	2	0.68	0.34	10.21	0.0063*
Temporal Epoch (T)	2	0.90	0.45	12.94	0.0031*	2	0.54	0.27	17.74	0.0011*
Subjects (S)	4	2.41	0.60			4	0.84	0.21		
W*T	4	0.02	0.00	0.39	0.81	4	0.05	0.01	0.80	0.54
W*S	8	0.16	0.02			8	0.27	0.03		
T*S	8	0.28	0.03			8	0.12	0.02		
W*T*S	16	0.18	0.01			16	0.23	0.01		
Total	44	4.08				44	2.73			

EMS: expected mean square

Table 3. The repeated measure ANOVA for saccadic net yield in both tasks (Fig 9)

	# target /s in the estimation task					# target /s in the Look-only task				
Source of Variance	***df***	***SS***	***EMS***	***F***	***p***	***df***	***SS***	***EMS***	***F***	***p***
Circle Width (W)	2	7.84	3.92	97.78	<0.01*	2	8.78	4.39	39.90	0.0001*
Temporal Epoch (T)	2	0.04	0.02	1.25	0.34	2	0.29	0.15	4.62	0.0463*
Subjects (S)	4	0.94	0.23			4	0.51	0.13		
W*T	4	0.11	0.03	4.92	0.0089*	4	0.08	0.02	1.23	0.34
W*S	8	0.32	0.04			8	0.88	0.11		
T*S	8	0.13	0.02			8	0.25	0.03		
W*T*S	16	0.09	0.01			16	0.26	0.02		
Total	44	9.48				44	11.05			

EMS: expected mean square

Table 4. The repeated measure ANOVA for saccadic dwell time in both tasks (Fig 10)

	Dwell times in the estimation task					Dwell times in the Look-only task				
Source of Variance	***df***	***SS***	***EMS***	***F***	***p***	***df***	***SS***	***EMS***	***F***	***p***
Saccade starting location (A)	1	119873.80	119873.80	46.90	0.0024*	1	113981.80	113981.80	152.39	0.0002*
Saccade landing location (B)	1	886.30	886.30	6.74	0.06	1	1582.40	1582.40	16.95	0.0147*
Width (W)	2	26195.80	13097.90	21.68	0.0006*	2	32475.90	16237.95	21.15	<0.001*
Subjects (S)	4	43201.10	10800.28			4	9024.60	2256.15		
A*B	1	3199.90	3199.90	22.16	<0.001*	1	272.50	272.50	2.24	0.15
A*W	2	2102.50	1051.25	7.28	0.0026*	2	264.00	132.00	1.08	0.35
A*S	4	10224.30	2556.08			4	2991.90	747.98		
B*W	2	567.90	283.95	1.97	0.16	2	5.30	2.65	0.02	0.98
B*S	4	526.10	131.53			4	373.50	93.38		
W*S	8	4833.70	604.21			8	6141.10	767.64		
Error	30	4332.00	144.40			30	3652.60	121.75		
Total	59	215943.40				59	170765.60			

EMS: expected mean square

Table 5. Dwell time for 4 groups of primary saccades and landing accuracy.

	Width	*Leaving from a target*							*Leaving from a distractor*						
		Going to a Target			*Going to a Distractor*			*P(hitting a target)*	*Going to a Target*			*Going to a Distractor*			*P(hitting a target)*
		Mean	*SE*	*N*	*Mean*	*SE*	*N*		*Mean*	*SE*	*N*	*Mean*	*SE*	*N*	
EV	W5	311	8.61	187	303	10.66	123	0.60	199	6.99	167	205	7.91	160	0.51
	W6	260	3.56	377	262	7.94	112	0.77	127	4.96	157	141	6.2	79	0.67
	W7	238	2.92	557	230	10.8	48	0.92	117	5.2	104	130	11.78	21	0.83
KM	W5	217	10.02	64	211	8.25	140	0.31	188	6.36	147	201	5.06	260	0.36
	W6	217	4.53	304	209	8.95	132	0.69	153	4.81	184	172	6.79	86	0.68
	W7	208	3.45	462	187	6.79	71	0.87	129	6.01	130	159	11.41	39	0.77
MJB	W5	299	8.67	145	286	9.55	126	0.54	197	7.41	152	209	7.29	176	0.46
	W6	265	4.76	316	250	8.46	114	0.73	135	4.84	157	172	11.63	64	0.71
	W7	235	3.64	381	247	13.96	77	0.83	134	5.69	118	202	16.32	39	0.75
VK	W5	225	3.66	276	234	4.58	252	0.52	159	4.34	287	167	4.52	237	0.55
	W6	226	2.31	616	226	5.54	135	0.82	120	3.94	189	139	7.34	91	0.68
	W7	225	2.08	709	229	6.24	106	0.87	100	4.07	151	133	11.82	40	0.79
BS	W5	344	10.12	95	334	10.16	98	0.49	261	9.47	110	253	9.38	104	0.51
	W6	309	4.93	251	297	9.42	45	0.85	179	10.32	71	194	13.02	27	0.72
	W7	313	4.44	318	281	13.23	38	0.89	134	6.72	62	190	32.8	6	0.91

T: Target; D: distractor

Table 6. The repeated measure ANOVA for target eccentricity in both tasks (Fig 11).

	Eccentricity in the Estimation task					Eccentricity in the Look-only task				
Source of Variance	***df***	***SS***	***EMS***	***F***	***p***	***df***	***SS***	***EMS***	***F***	***p***
Ordinal Position (P)	5	505663.5	101132.70	111.88	<0.001*	5	613707.2	122741.44	133.42	<0.001*
Accuracy: Hit or Miss (A)	1	54288.5	54288.50	15.52	0.017*	1	138783.4	138783.40	61.88	<0.001*
Width (W)	2	52307	26153.50	30.95	<0.001*	2	36839.2	18419.60	9.46	0.0078*
Subjects (s)	4	4542.8	1135.70			4	12131.6	3032.90		
P*A	5	9925.3	1985.06	4.46	<0.001*	5	27586.1	5517.22	7.42	<0.001*
P*W	10	17386.7	1738.67	3.91	<0.001*	10	13394.1	1339.41	1.80	0.07
P*S	20	18078.3	903.92			20	18399	919.95		
A*W	2	2780.3	1390.15	3.12	0.048*	2	4731.1	2365.55	3.18	0.045*
A*S	4	13994.8	3498.70			4	8971.8	2242.95		
W*S	8	6760.6	845.08			8	15575.5	1946.94		
Error	118	52538.3	445.24			118	87737.6	743.54		
Total	179	738266.1				179	977856.6			

EMS: expected mean square

Table 7. The repeated measure ANOVA for saccadic dwell time in both tasks (Fig 12).

	Dwells in the Estimation task					Dwells in the Look-only task				
Source of Variance	***df***	***SS***	***EMS***	***F***	***p***	***df***	***SS***	***EMS***	***F***	***p***
Ordinal Position (P)	5	102148	20429.50	15.98	<0.001*	5	94856.90	18971.38	19.71	<0.001*
Accuracy: Hit or Miss (A)	1	1466.9	1466.90	3.39	0.14	1	1.60	1.60	0.00	0.95
Width (W)	2	7891.3	3945.65	5.74	0.0285*	2	20397.70	10198.85	8.93	0.0092*
Subjects (s)	4	116788	29196.95			4	17491.20	4372.80		
P*A	5	8945.8	1789.16	8.42	<0.001*	5	7415.40	1483.08	4.21	0.0015*
P*W	10	9271.3	927.13	4.36	<0.001*	10	10766.00	1076.60	3.05	0.0018*
P*S	20	25562.7	1278.14			20	19250.20	962.51		
A*W	2	725.6	362.80	1.71	0.19	2	672.40	336.20	0.95	0.39
A*S	4	1732.3	433.08			4	1306.40	326.60		
W*S	8	5501.7	687.71			8	9141.80	1142.73		
Error	118	25079	212.53			118	41604.50	352.58		
Total	179	305112				179	222904.10			

EMS: expected mean square

Table 8. The repeated measure ANOVA for saccadic dwell time in Experiment 2 (Fig 14).

Source of Variance	***df***	***SS***	***EMS***	***F***	***p***
Circle Width (W)	2	2111.7	1055.85	3.50	0.07
Contrast (C)	2	3493.4	1746.7	5.66	0.02*
Subjects (S)	5	14740.3	2948.06		
W*C	4	357.2	89.3	3.46	0.03*
W*S	10	3017.5	301.75		
C*S	10	3087.4	308.74		
W*C*S	20	516.4	25.82		
Total	53	27323.9			

EMS: expected mean square

Table 9. Repeated measures ANOVA for saccadic selectivity in Experiment 2 (Fig 14).[2]

Source of Variance	***df***	***SS***	***EMS***	***F***	***P***
Circle Width (W)	2	3.16	1.58	71.91	<0.001*
Contrast (C)	2	0.00	0.00	0.39	0.69
Subjects (S)	5	1.74	0.35		
W*C	4	0.01	0.00	0.98	0.44
W*S	10	0.22	0.02		
C*S	10	0.04	0.00		
W*C*S	20	0.04	0.00		
Total	53	5.21			

EMS: expected mean square

[2] The reported statistics are based throughout on the angular transformation, $g(y) = 2\arcsin\sqrt{y} - (\pi)/2$, applied to the normalized smoothing measure (which ranges from 0 to 1) in order to improve the normality of its distribution (Hoaglin, Mosteller, & Tukey, 1991).

Table 10. Repeated measures ANOVA for saccadic dwell time in Experiment 2 (Fig 15)

Source of Variance	***df***	***SS***	***EMS***	***F***	***p***
Starting location (A)	1	493916.70	493916.70	45.12	0.001*
Landing location (B)	1	7510.00	7510.00	16.31	0.01*
Circle Width (W)	2	69018.70	34509.35	18.86	<0.001*
Contrast (C)	2	11586.10	5793.05	5.20	0.03*
Subjects (S)	5	65681.00	13136.20		
A*B	1	22449.60	22449.60	71.99	<0.001*
A*W	2	7776.10	3888.05	12.47	<0.001*
A*C	2	4104.70	2052.35	6.58	0.002*
A*S	5	54728.70	10945.74		
B*W	2	1040.30	520.15	1.67	0.19
B*C	2	723.20	361.60	1.16	0.32
B*S	5	2302.10	460.42		
W*C	4	1141.50	285.38	0.92	0.46
W*S	10	18293.10	1829.31		
C*S	10	11137.10	1113.71		
Error	161	50205.50	311.84		
Total	215	821614.40			

EMS: expected mean square

7. **Appendix**

A. Ideal Selectivity

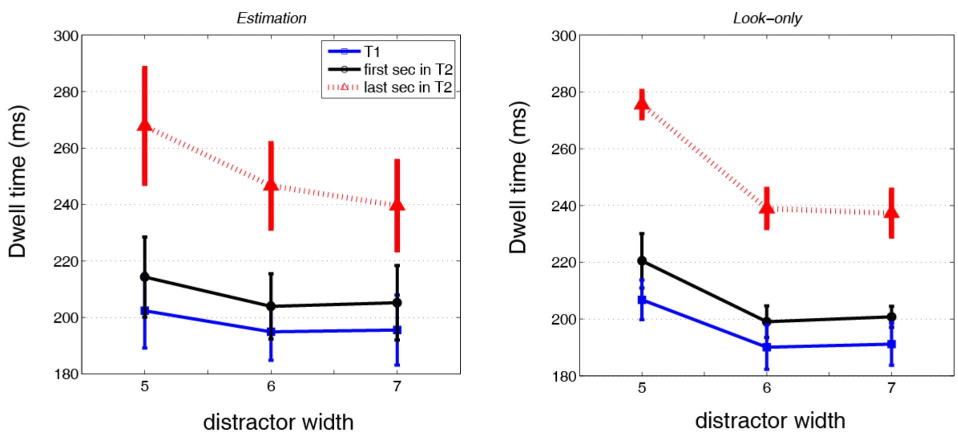
The preliminary psychophysical experiment had shown that subjects visual acuity for the current display depended on both circle eccentricity and distractor circle width. That is, for each difficulty of selection, the ability to identify the circle depends on its eccentricity. By using this function, the physical stimulus display can be converted to a stochastic visual array based on the eccentricity of each circle relative to current fixation. If a circle i was a target and its eccentricity from current fixation was E_i , the probability of recognizing this circle as a target was $P(E_i)$ based on the function of visual acuity. On the other hand, if a circle j was a distractor and had an eccentricity E_j, the probability of recognizing this circle as a distractor was $P(E_j)$ and the probability of perceiving this circle as a target was $1- P(E_j)$. By using the function of visual acuity, each circle in the display would have its own probability of being regarded as a target. Then we could redefine the identity of each circle by drawing a sample from a binomial distribution with the parameter $P(E_j)$ if the circle was a target, or with the parameter $1- P(E_j)$ if the circle was a distractor. This transformed visual array could be treated as the perceptual display subjects perceived instead of the ground truth physical display. Since the eccentricity of each circle changes after each saccade, the stochastic perceptual display has to be recomputed after each saccade as well. This method allows us to compare subjects' saccadic selectivity and the best performance they could make only based on the visual acuity during the search sequences.

To simulate saccadic selectivity, this process was repeated 10,000 trials for each selection difficulty, and each trail was assumed to have 6 saccades (3 saccades/sec). In addition, the model assumes that each saccade was aimed to the nearest target circle in the perceptual display.

Saccadic selectivity was calculated by the proportion of target circles fixated in the perceptual display were the actual target circles in the true display before the transformation. Figure 7 shows the average of simulation results from each subject *(Star signs in Figure 7).* Notice that the model assumed that each saccade only looked for one target circle at a time and no information would be carried to the subsequent saccades.

B. Saccadic dwell time

In addition to scanning rates, saccadic pause interval can also reveal the strategy of saccadic planning during search sequences. *FigureA1* analyzes saccadic timing by a related measure, the dwell time between consecutive primary saccades, rather than saccade rates. Dwell time is defined as the pause time between two consecutive primary saccades (see example in *Figure 4*), minus the in-flight time of any secondary saccades (Wu et al., 2010).



FigureA1. Dwell time of primary saccades as a function of distractor width in the statistical estimation task and the look-only task. Three different lines represent 3 temporal epochs (blue: 1 s trial; black: first second of the 2 s trial; red: last second of the 2 s trial). Bars show ± SE; otherwise, SE's are smaller than the plotting symbols.

Increasing the discriminability of targets and distractors decreased dwell times by about 30 ms in later epoch of both tasks (*FigureA1*, red lines).

C. A proposed test for the ideal timer

One of biggest findings in the present study is that people use an internal timer rather than the accumulated evidence to determine when to initiate next saccade. When the deadline of the timer was reached, people would make a saccade to another location, regardless of whether the new location is informative or not. In agreement with prior studies (Araujo, Kowler, & Pavel, 2001; Hooge & Erkelens, 1998, 1999), the result seems to suggest that people prefer a rapid scanning rate to careful planning in saccadic guidance, and the strategy used to choose where to saccade is suboptimal.

An ideal search strategy should be able to apportion time between target selection and saccade production rates. To do this, the system needs to integrate eccentric information to determine how fast the scanning rate should be during the sequence of scanning. A suboptimal search strategy may imply people are not able to maximize the utility of eccentric information to make saccadic decisions, and thus the visual system has to increase the frequency of fixations to get more information. Morvan and Maloney (2012) have shown that people were not able to use the eccentric information to minimize the number of saccades in visual search. Another possibility is that eccentric information could be properly analyzed but the system chooses not to do so due to higher cost of cognitive load. Since there is no visible cost for the incorrect selection, saccades can be made to a known trivial location for other reasons, such as a large target eccentricity (Wu, Kwon, & Kowler, 2010).

Some prior studies have found that people could take visual and motor uncertainties into account and make an ideal movement decision when the cost of reckless planning was explicit (Battaglia & Schrater, 2007; Hudson, Maloney, & Landy, 2008; Trommershäuser, Maloney, &

Landy, 2003a, 2003b). It may be possible that the visual system is able of using eccentric information to guide saccades when the cost of incorrect selection is noticeable. One of the difficulties in investigating this question is the concurrent visual process. That is, during each intersaccadic interval, the system has to process the currently fixated content and select where to look next. It is hard to dissociate how much time is actually spent accumulating eccentric information to achieve better accuracy of target selection.

The following suggested experiment is attempting to understand whether the faster scanning strategy found by prior studies is due to the inability of using eccentric information, or to the reluctance to do further processing. I am interested in the question: Can the visual system maximize the utility of eccentric information to correctly guide saccades?

This new experiment minimizes the foveal analysis load, uses an eccentric stochastic stimulus to indicate an alternate target location, and includes the cost for the incorrect selection.

METHODS

STIMULUS DISPLAY

The stimulus display contained 4 unfilled squares (*Figure A2*). Three of squares were located at the corners of an imaginary equilateral triangle, and the other square was located at the center of the triangle. To minimize the load of analyzing the fixated content, there would be only a cross inside each corner square. These fixation crosses helped subjects maintain their fixation inside the squares. A random dot motion stimulus is placed inside the central square. The only manipulated variable in the random dot motion is the dot contrast. The dot contrast is initially the same as background contrast and its luminance will constantly increases over time once the stimulus is initiated (1 cd/70 ms*). The other variables affecting the perception of random dot motion are constant (dot numbers = 20; motion coherence = 40%, dot size = 10; dot moving velocity = 10 deg/s).

PROCEDURES

At the beginning of each trial, subjects will be instructed to fixate the central square then saccade to the lower square. Once the lower square is fixated, the random dot motion stimulus appears inside the central square. The direction of random dot motion indicates which one of the other two squares is the target that subjects should look to next. The random dot motion terminates once one of two squares is fixated. If the fixated square is the square indicated by the random dots motion (correct selection), a new random dot motion stimulus would be reinitiated immediately, and indicating one of the other non-fixated squares. On the other hand, if the other square is fixated (incorrect selection), there would be a delay cost such that the new random dots motion stimuli would not start until the delay time is reached. In addition, the motion will be terminated when subjects fixate anywhere outside of three corner squares.

Subjects will be instructed to use their eccentric vision to gather the information about subsequent target location based on the direction of random dot motion. Trial duration is set to 15 seconds and subjects are told to scan as many target squares as possible. The delay cost for each incorrect selection is set one of four values (500, 1000, 1500, 2000 ms).

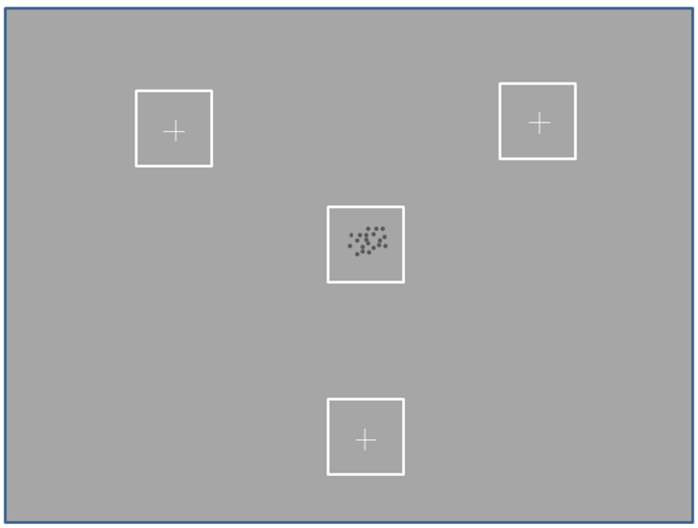


Figure A2. Stimulus display. A random dot motion stimulus would appear inside the center square.

IDEAL OBSERVER

To maximize the numbers of target fixated during the sequence, observers need to take into account the cost of incorrect selection rather than scan at their highest rate and make a random choice. For any single saccadic decision, the probability of looking at target square is determined by the information accumulated function F(t) where the t is the saccadic pause duration in our task. This accumulated probability function is an increasing function of t and is shown in *Figure A3*.

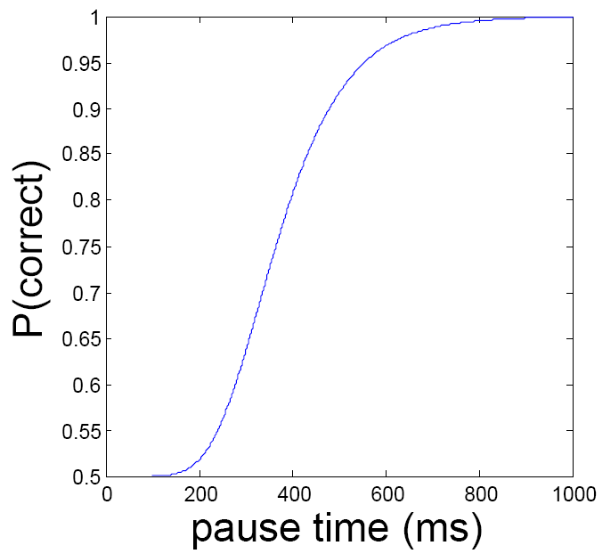


Figure A3. Probability of selecting the target as a function of saccadic pause duration.

The ideal observer should be able to use the accumulated function of t and take into account the potential time cost C for the incorrect selection. By using the accumulated function and the potential cost, we can calculate the expected pause duration for each single saccadic decision t_{exp}. That is, given a fixed pause duration t, the corresponding probability of finding the target is P(t). Thus, the probability of choosing the non-target square is 1-P(t) and the expected time cost becomes [1-P(t)]* C. Given a pause duration and expected time cost, we could find the expected pause duration t_{exp}.

$$t_{exp} = t + [1-P(t)] * C \qquad \text{--- (1)}$$

Figure A4 shows that the expected time t_{exp} varies with the actual pause duration and the cost for the incorrect selection. When the cost is small, the best strategy is scanning as fast as they can without considering the accuracy of selection (ex. Cost = 500 ms). On the other hand, when the cost becomes higher, scanning at their highest rate may not be a good strategy. The ideal observer should be able to evaluate the cost and find proper pause time t which minimizes the expected pause duration t_{exp} so that more targets can be found during the scanning sequence (black circles in the *Figure A4*).

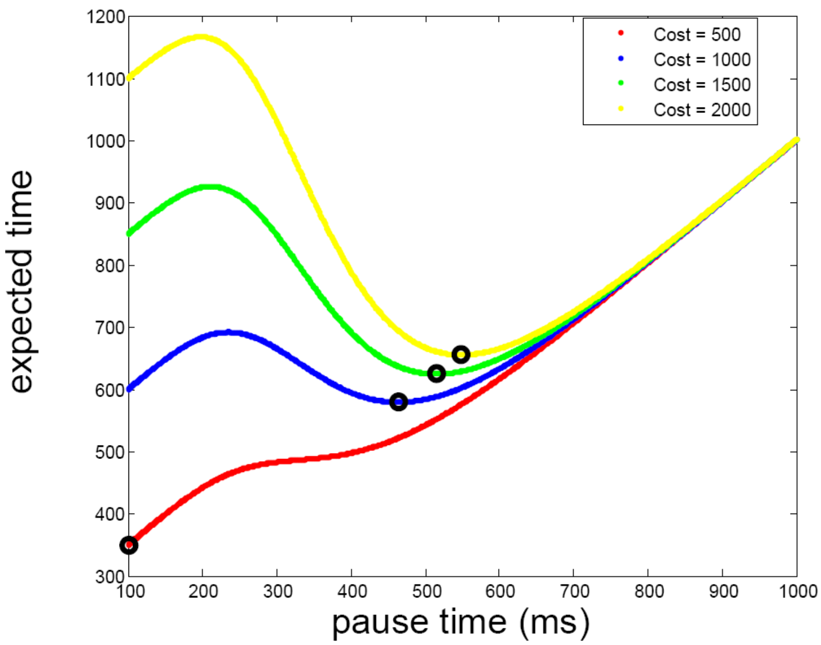


Figure A4. Expected pause duration as a function of actual saccadic pause duration for different levels of time cost. The black circles indicated the minimum expected time for each time cost.

Prediction:

If human observers can maximize the utility of eccentric information, they should be able to choose the similar pause durations as predicted by ideal observer (black points in Figure A4).

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