MICRO-PURSUIT AND STRATEGIES OF ALLOCATING ATTENTION DURING

VISUAL TASKS WITH MOVING TARGETS

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ABSTRACT OF THE THESIS

Micro-pursuit and strategies of allocating attention during visual tasks with moving targets

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Eye movements are often studied in the context of demanding visual tasks in which goals are achieved on the basis of the visual information gathered from sequence of fixations (Hayhoe, 2017). Much less attention has been devoted to how smooth pursuit is used during visual or visuomotor tasks. Prior studies investigated the link between smooth pursuit eye movements and manual interception. Results showed that pursuing a moving target was beneficial to estimate the time of the interception and larger tracking errors resulted in larger interception errors (Brenner and Smeets, 2011; Fooken et. al., 2016). The present study examined eye movement strategies and perceptual performance in a demanding visual task involving moving targets (discs), modeled after the judgments at traffic circles. The task required judgments of relative motions of two targets heading to a common meeting point, specifically, how much faster is one target relative to the other. The questions intended to be resolved are, what is the eye strategy used spontaneously during the course of the motion, and is the chosen eye strategy indeed the better eye strategy to use while judging the relative motions? Two motion discrimination tasks were assigned by blocks to all four subjects: (1) the which-first task requiring judging which disc would arrive the meeting point first and (2) the more challenging collision task requiring judging which disc would arrive first and whether the two discs would collide at the meeting point. Collision was defined as any overlapping of two discs. Subjects performed both tasks under a free-viewing condition, in which they received no instructions about where to look or whether to pursue either moving disc (Experiment 1). Perceptual results show that people can precisely judge the relative motions, with Weber fractions ranging from 3-6%. Three-dimensional representations were created showing the distributions of both averaged horizontal eye position (x-axis) and horizontal eye velocity (y-axis) at different epochs of time. This novel analysis allows comparisons between eye velocities and positions over time so that the sources of position change (saccades or pursuit) can be distinguished. Eye movement results show that the preferred eye strategy was to fixate near the meeting point and pursue the pair of the discs after the decision was made, anticipating the motion of the paired discs on the last lag of the display. The influences of the standard disc velocity and the comparison disc velocity on the averaged eye velocity at different representative times suggest that fixate was achieved at least in part by dividing attention between discs moving in opposite directions during the time the decision was being made. To better capture the effectiveness of the preferred eye strategy. All subjects performed the same tasks with the strategies determined by instructions (Experiment 2): (1) fixating near the meeting

point or (2) switching between discs while making decisions. Performance of all four subjects showed precise discrimination for both tasks (which-first and collision) and both eye strategies (fixate and switch), with Weber fractions ranging from 2-5%. Better discrimination was obtained with the fixate strategy (2.94%) than the switch eye strategy (4.14%). Results were consistent in the collision task, indicating the fixate strategy led to better discrimination when judging the relative motion of the two discs heading toward the same meeting point.

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1. Introduction

Eye movements are often studied in the context of demanding visual tasks in which goals are achieved on the basis of the visual information gathered from different patterns of eye movements (Hayhoe, 2017). Most investigations have focused on the planning of saccadic eye movements. Factors that influence saccadic planning include the value of the information, reward obtained, cognitive effort expended to plan the movements, or tradeoffs between reliance on fixations and reliance on retrieval from memory (e.g., Najemnik and Geisler, 2005; Eckstein, 2011; Rubinstein and Kowler, 2018; Ballard et. al., 1995; Epelboim and Suppes, 2001).

Much less attention has been devoted to the role of smooth pursuit eye movements during visual or visuomotor tasks. Smooth pursuit is used to track smoothly moving targets, ensuring that the motion of the target on the retina is suitable for supporting clear vision (Kibbe and Kowler, 2011; Krauzlis, 2004, Kowler et. al., 2019). Studies of smooth pursuit typically avoid including a visual task or judgment. Exceptions are studies that examined the role of pursuit in ensuring adequate spatial resolution of target. (Murphy, 1978, Schütz et. al., 2008, Palidis et. al., 2017); or smooth pursuit during visual or visuomotor tasks determining whether pursuit (either instructed or spontaneous) improved task performance. Some examples of these studies are summarized below.

Spering et. al. (2011) studied instructed pursuit during tasks in which decisions were made under different levels of certainty. The task required judging whether a small ball on one side of a display would either hit or miss a line segment (the goal) on the other side. Observers were instructed either to smoothly pursue the target ball traveling toward the stationary goal, or to fixate the stationary ball while the goal moved toward the target ball. Both the ball and the goal were removed before the hit or miss event, thus allowing perceptual judgments to depend on the ability to extrapolate the target's visual trajectory. Perceptual performance was found to be better with pursuit than fixation, suggesting a role of pursuit in predicting motion. Spering et. al. (2011) attributed the better prediction of motion during pursuit to internal motor signals coming from activity in the supplementary eye field (SEF), which has a role in generating anticipatory pursuit (Missal and Heinen, 2004; de Hemptinne, et. al., 2008).

Fooken et. al. (2016) extended this work, investigating the link between pursuit eye movements and manual interception. Subjects were told to smoothly track a small moving dot, and manually intercept it with their finger as quickly and accurately as possible when the target entered a "hit zone". Results showed that larger tracking errors resulted in larger interception errors, suggesting a helpful role for pursuit in manual interception. Fooken et. al. (2018) used the same task to test the transferability of training between eye and hand. They found that the manual interception accuracy was improved when the eye and the hand were trained simultaneously, implying that training of pursuit eye movements, by itself, is not sufficient to improve the accuracy of hand movements (Fooken et. al., 2018).

Brenner and Smeets (2011) studied the interception of a moving target with a stylus across the surface of a drawing tablet. They did not give explicit eye movement instructions. The tasks were either to (1) hit a small moving target so that it landed inside a large gap, or (2) move a cursor so that it intercepted a large target moving behind a small gap. Subjects preferred to fixate the smaller object in both tasks. Specifically, they spontaneously pursued the small moving target when they had to hit the small target into the large gap, whereas they fixated the small gap when they had to hit the large target moving behind the small gap. Subjects were more accurate at intercepting the target in the second task, where they spontaneously fixated the small gap. However, the precision of the timing of the hit was higher in the first task, where subjects pursued the small target, implying that pursuing the moving target was beneficial to estimating the time of the hit.

Land and McLeod (2000) found a role for spontaneous pursuit during cricket playing. They compared the eye movement strategies used by cricket players with different skill levels, where the players were instructed to hit a ball launched from a bowling machine. The ball could bounce at different distances. Players used similar eye strategies despite their different skills: they fixated where the ball was launched for a short period of time after the launch, then made a predictive saccade downward to fixate the location on the ground where they believed the ball would bounce. Pursuit of the ball occurred after the bounce and continued until the ball was hit. The player with the highest skill initiated the predictive saccade much faster and exhibited pursuit tracking of the moving target more often than other players, whereas the players with poorer skills responded more slowly, with variable saccadic initiation times, and relied more on a combination of the saccades and pursuit to track the moving target. These results suggested that pursuit to some extent reflected the skill of cricket players. Their results are consistent with other studies that supported a role of pursuit in tasks requiring manual interception of a moving objects (Cesqui et. al., 2015).

Diaz, Cooper, Rothkopf and Hayhoe (2013) extended the work to investigate the information used for prediction. Subjects played racquetball in a virtual environment with their eye movements being recorded. Similar eye strategies to those reported by Land and McLeod (2000) were found except that the initial saccade resulted in a fixation location above the future bounce position of the ball. Diaz, Cooper, Rothkopf and Hayhoe (2013) also suggested that pursuit following the initial saccade may help to predict the future location of the target, thereby facilitating successful interception.

Despite these examples of spontaneous or useful pursuit during visuomotor tasks, other studies that required judgement of moving stimuli relative to stationary objects either did not observe spontaneous pursuit, or did not find that pursuit was useful. Spontaneous pursuit, for example, was not found while threading a virtual needle (Ko, Poletti & Rucci, 2010), when grasping a physical bar and moving it to a designated position (Johansson et. al., 2001), or when navigating a cursor through a virtual maze in overhead view (Kowler et. al., 2014). These results indicate that any possible advantage of pursuit in improving the visual clarity of the target may have been offset by other factors when the task requires judging the position of a visual target with respect to stationary details in the visual environment.

Taken together, prior studies indicate that the utility or value of pursuit in visual or visuomotor tasks is not yet resolved. Pursuit may be important for controlling the target’s image motion when judging a single object or intercepting a single moving object because it helps to perceive or anticipate changes in the trajectory of target motion. When prediction of motion is not necessarily required, for example, when judging a single moving object relative to a stationary object, the choice of fixation position may be more important (Ko, Poletti & Rucci, 2010; Johansson et. al., 2001; Kowler et. al., 2014). Also, pursuit may be less important when the motion of the moving object is self-generated (as it was in the three studies above) so that observers had completely control over the target motion. In addition, these tasks also required information about the location where the motion ended, a location that was part of the stationary structure or was designated by the experimenter. Thus, fixation in these tasks could help to improve the visual clarity of the end position so that the moving target could reach it successfully.

Management of eye strategies may be more complex when multiple moving objects are present simultaneously (e.g., Fehd and Seiffert, 2010). Under those circumstances, the observer has more freedom to choose the eye strategy. When pursuing one moving object exclusively, pursuit improves the visual resolution of the tracked object at the expense of others for extended periods of time, especially in a dynamic environment where the positions of all moving objects are constantly changing. When fixating a central location, on the other hand, fixation may improve the spatial resolution of all objects, but to a lesser degree. A strategy of switching between pursuit of different objects may improve visual clarity but benefit of pursuit might also be offset by time and effort involving planning the sequential switches in eye position as well as the momentary reduction in acuity during the saccades themselves. Thus, in a dynamic environment where multiple objects are moving at the same time the observer needs to decide the appropriate eye strategy to effectively gather needed information and balance the benefits of such eye strategy with its potential cost.

The goal of the present study was to examine eye movement strategies and perceptual performance in visual tasks involving two moving targets. Two tasks were studied. The “which-first” task required judgements of which target will arrive first. This is a 2AFC task, similar to that used in psychophysical studies of motion discrimination. The “collision” task asked for judgment about whether the target would collide at a meeting point. This 3AFC task was inspired by many real-world motion judgments, such as decisions about whether to stop or go at a traffic circle, which are made by judging how much faster one object is relative to another. Possible eye strategies involved: (1) pursue one of the objects, (2) switch between pursuit of different objects, or (3) fixate a central location. The main questions were: when free to choose the eye movement strategy (Experiment 1), did people spontaneously use the strategy associated with better perceptual performance (Experiment 2) and did that strategy involve any spontaneous pursuit (Experiment 1 and 2)?

2. Methods

2.1. Eye movement recording

Eye movements were recorded using the EyeLink 1000 (SR Research, Osgoode, Canada), tower-mounted version, sampling at 1000 Hz. A chin rest was used to stabilize the head. Viewing was binocular and eye movements were recorded from the right eye.

2.2. Subjects

Four undergraduate students (paid volunteers) at Rutgers University were recruited for the experiment. All had normal vision and were naïve to the purpose of the experiment. All experimental procedures were approved by the Rutgers University Institutional Review Board and adhered to the Declaration of Helsinki.

2.3. Stimuli

Stimuli were displayed on a Dell U241 LCD monitor (Round Rock, TX), 1280 x 1024 pixel resolution (28.2 x 22.5 deg at a viewing distance of 60 cm), with a refresh rate of 60 Hz. Stimuli were viewed in a fully lighted room and the boundaries of the display were visible.

Displays consisted of a white outline drawing of diamond-shaped "traffic circle", with a runway on each side, displayed on a black background (Fig. 1). Two discs (standard, red; comparison, green) moved through the traffic circle, starting from the beginning of the short (standard disc) or the long runway (comparison disc) and moving toward a common location, referred to as the meeting point, at the end of the long runway. The dimensions of the stimulus, the starting locations and the paths of the discs, and the location of a central fixation cross (which was removed shortly after the onset of trials) are shown in Fig. 1. The velocity of the standard was 5.28 deg/s. The velocity of the comparison was chosen at random from one of 11 equally-spaced (spacing 1.32 deg/s) values ranging from 4.62 deg/s to 5.94 deg/s.

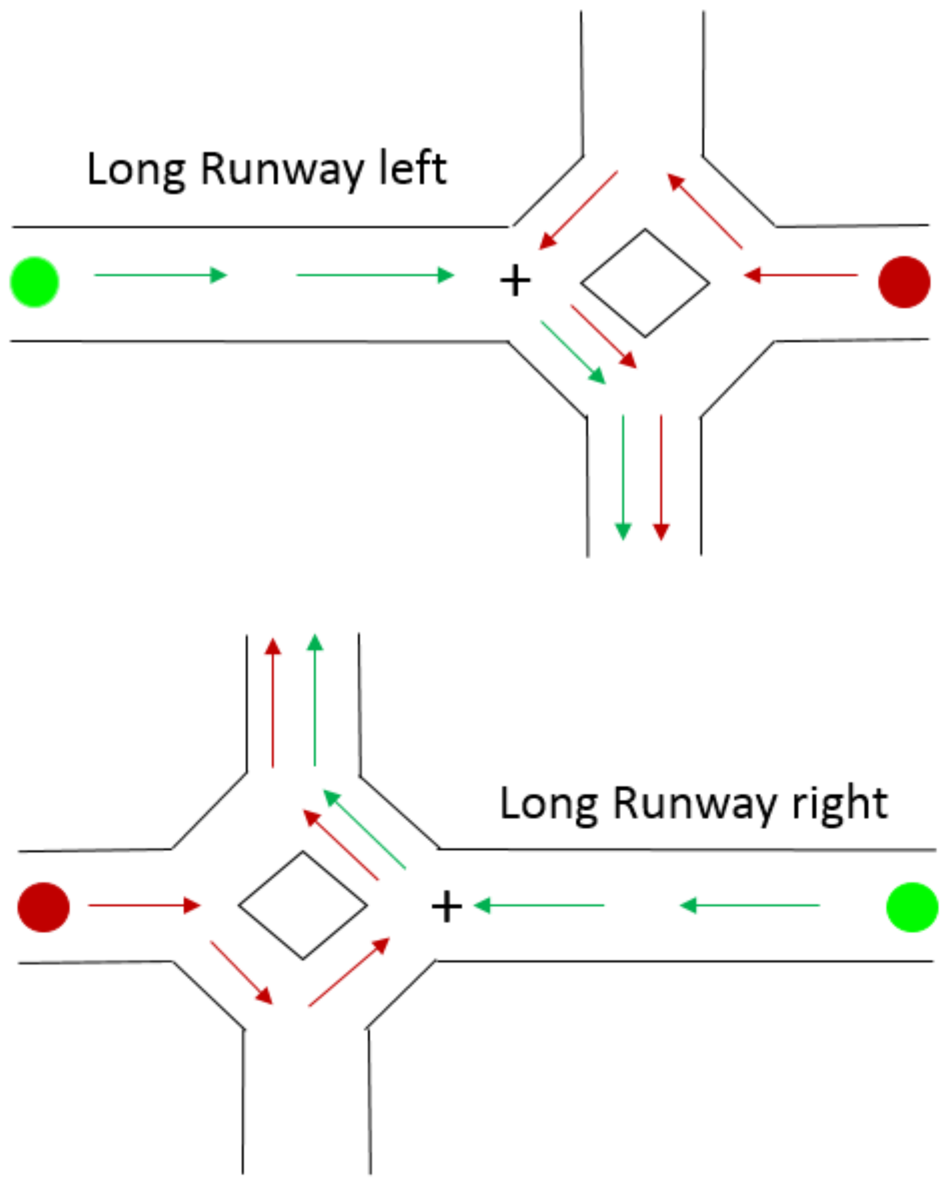


Figure 1. Displays of traffic "diamond" and two stimuli. The long runway could be either on the left or on the right. The red disc is the standard, which is always moving on a short runway at a constant velocity (5.28 deg/s). The green disc is the comparison. Its velocity was randomly chosen in the range (4.62 to 5.94 deg/c). The path of each disc was not shown to the subjects but is color-coded here for illustration purpose. The central fixation cross appeared with the display for 1 s and then was removed.

2.4. Procedure

Subjects fixated the fixation cross and started each trial when ready by means of a button press. The fixation cross disappeared after a delay of 500 ms and was replaced by the traffic circle with the standard and comparison discs at their start locations. Trials with the long runway on the left or on the right were run in blocks of 240 trials (for subjects SS and JG) or blocks of 160 trials (for subjects MN and EM). After a delay of 1 s both discs began moving toward the meeting point. In the "which first" task, subjects were asked to press one of two buttons to indicate which disc (standard/red or comparison/green) would arrive at the meeting point first. In the "collision" task subjects were asked to press one of three buttons to indicate whether (1) the discs would collide, (2) the red disc would arrive first, or (3) the green disc would arrive first. The two tasks were tested in separate blocks of 120 trials (for SS, JG) or 80 trials (for MN, EM).

A collision was defined as any overlap in the disc positions when they arrived at the meeting point. At the velocities tested, a collision occurred for the central 5 values of the comparison disc where disc velocities differed by < about 10%. Responses had to be made before either disc reached the meeting point, otherwise the trial was not included. Discs continued along the paths after the response, with both discs traveling toward the same exit of the traffic circle (Fig. 1). At the end of the trial, feedback was given to inform subjects which disc arrived at the meeting point first, whether a collision occurred, and their response time. For trials in which responses were given too late, the response time displayed as part of the feedback was 0.

2.4.1. Experiment 1: Free viewing

In the free viewing experiment subjects were given no instructions about where to look or whether to pursue either moving disc.

2.4.2. Experiment 2: Fixate vs. switch

In the fixate vs. switch experiment, instructions were either to: (1) fixate the meeting point, or (2) switch between fixation of either disc. Instructions applied only to the period prior to making the report. For the switch instruction subjects were told to try to spend about the same amount of time fixating each disc, but were not told when to make the switches or often to switch. Instructions were tested in separate blocks of 80 trials

2.4.3. Experimental sessions

Experiment 1: Experimental sessions consisted of 40 trials. The location of the runway (left or right) and the task (which first or collision) were the same throughout a session. Subjects SS and JG were tested in three consecutive sessions with the same task and 6 consecutive sessions with the same runway location. Subject MN and EM were tested in two consecutive sessions with the same task and 4 consecutive sessions with the same runway location. Subject SS was tested in 60 sessions over 10 days; JG in 78 sessions over 12 days; MN in 100 sessions over 10 days; and EM in 94 sessions over 12 days.

Experiment 2: The location of the runway and the tasks were the same as Experiment 1. The different eye movement instructions were tested in separate sessions, with all subjects running in two consecutive sessions with the same eye strategy and task (which first or collision) and 8 consecutive sessions with the same runway location. Subjects SS and JG completed all sessions of which-first task before starting the collision task. The task assignment was changed every 2 to 4 sessions for subjects MN and EM. SS was tested in a total of 38 sessions over 10 days; JG in 42 sessions over 10 days; MN in 36 sessions over 7 days; and EM in 40 sessions over 8 days.

2.5. Analysis

2.5.1. Analysis: Perceptual data

Which-first task. Perceptual performance of each subject in the which-first task was determined by psychometric functions showing the proportion of comparison-first reports as a function of the comparison velocity. Data from both runway locations (left or right) were pooled. Each psychometric function was fitted by the Weibull function using the algorithm (MATLAB, Mathworks, Natick, MA) in Lu and Dosher (2014) (p. 321-322). Standard deviations were determined by a bootstrapping method (Lu and Dosher, 2014, p. 324). Difference thresholds (delta-V) was calculated from the fitted Weibull functions as half the difference between the velocities corresponding to the 75% and at 25% performance levels. Biases to report standard or comparison first were determined from the 50% level of the fitted Weibull.

Collision task. In order to compare thresholds in the collision task with those of the which-first task, responses were collapsed into two categories in two different ways: (1) collision + comparison first vs. standard first; (2) collision + standard first vs. comparison first. This produced two psychometric functions for each condition, which were analyzed in the same way as the data from the which first task.

Improvements over sessions. Analysis of the performance on a session by session basis for Experiment 1 showed improvement over sessions and over days. To determine the rate of improvement, and when performance approached asymptotic levels, perceptual discrimination thresholds were determined for consecutive sets of 5 sessions (~200 trials) for each task (Fig. 2 shows the improvements over session sets). Testing continued until asymptotic performance was reached. Perceptual data described in the Results are based on the final 18 sessions for each task (which first; collision) when performance had reached asymptotic levels.

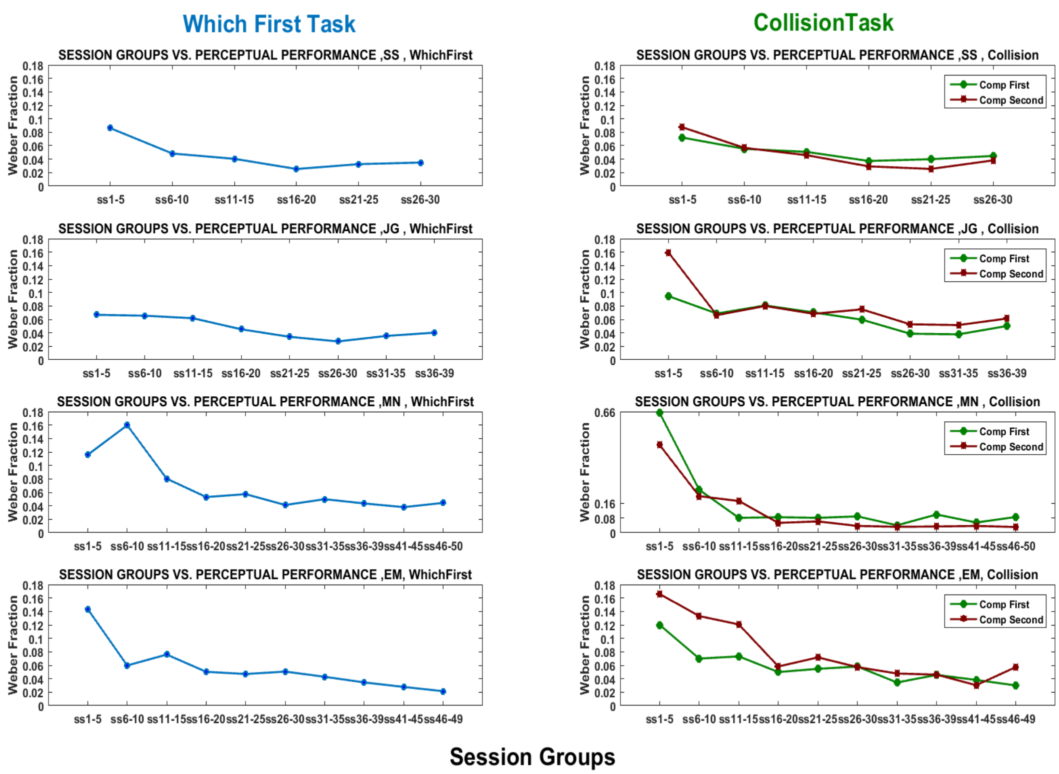


Figure 2. Learning curves from the which-first task (left column) and the collision task (right column) depicting Weber fractions as a function of session groups, four subjects, Experiment 1.

2.5.2. Analysis: Eye movement data

Analyses were performed using custom developed Matlab software (Mathworks, MA, USA). The onsets and offsets of saccades were determined offline by computing eye velocity during consecutive 13-ms samples, with onsets separated by 1 ms. Saccade onsets and offsets were detected using a velocity criterion that was determined and subsequently confirmed for each subject by examining a large sample of analog recordings of eye positions. The criterion was 11 deg/s for JG, MN and 18 deg/s for SS, EM.

Horizontal and vertical eye velocity was computed for 100 ms intervals with onsets of successive samples separated by 2 ms. Samples containing saccades, blinks, or portions of saccades or blinks were removed. Velocities were then averaged over time, from 500 ms before the motion onset to the end of the trial.

Horizontal and vertical eye positions for the same 100 ms intervals were also determined.

To pool eye movement data over the left and right runway locations, data from the runway on the left trials were rotated 180 degrees.

3. Results

3.1. Experiment 1: free viewing

3.1.1. Practice

Performance in the perceptual tasks, improved with practice. Figure 2 shows the Weber fractions as a function of sessions, where sessions are grouped into sets of five for each subject and for both the which-first and collision tasks. To facilitate comparisons across tasks, results for the 3-choice collision task are shown for the analysis in which the three possible responses (comparison disc arrives first vs. collision vs. comparison disc arrives second) were organized into two categories, either comparison disc arrived first vs. either collision or comparison disc arrives second, or comparison disc first or collision vs. comparison disc second (see section 2.5.1 in Methods). Figure 2 shows that Weber fractions decreased with repeated testing with most of the improvement occurring during the first 15-20 sessions. The analyses to be reported in the remaining results will therefore encompass the final 18 sessions for each task and each subject (the final 3-4 data points in Fig. 2), after stable levels of performance were reached.

3.1.2 Perceptual performance

Perceptual discrimination for the final 18 sessions showed very precise discrimination for both the which-first and the collision tasks, with Weber factions ranging from 3-6% (Fig. 3). The average Weber fraction was 3.75% (SD = 0.29) for the which-first task, 4.66% (SD = 0.38) for the collision task when responses were grouped as comparison disc first vs. collision+comparison second, and 4.28% (SD =

0.32) for when the responses were grouped as comparison first+collision vs. comparison second.

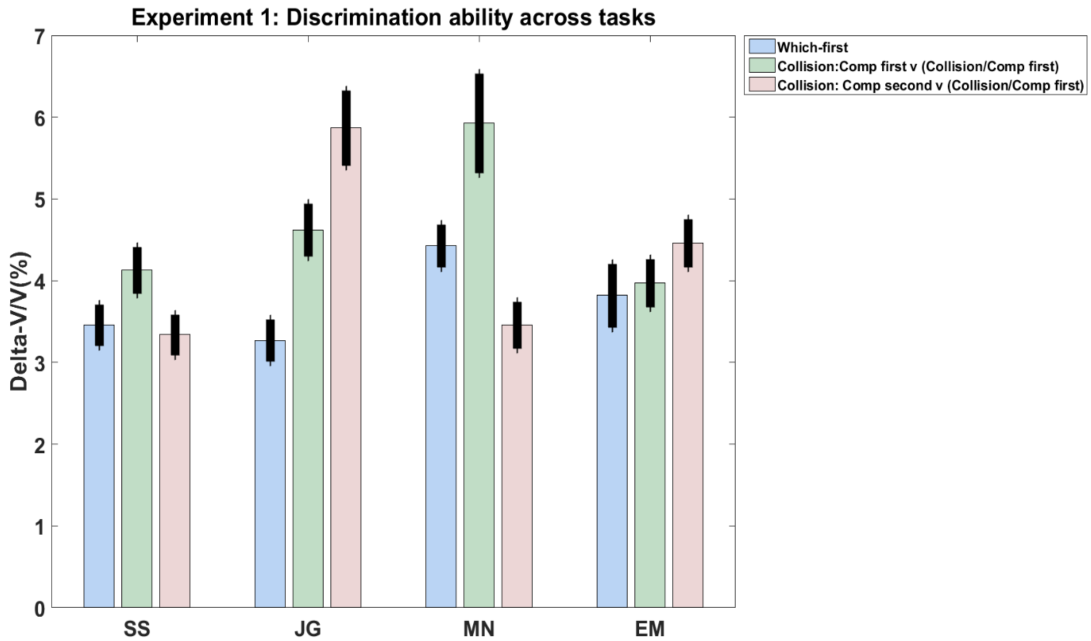


Figure 3. Perceptual discriminations assessed by Weber fractions from the which-first and the collision tasks, four subjects, Experiment 1.

Bias shown in Fig. 4, was defined as the difference between performance at the 50% point of the fitted psychometric function (see Methods 2.5.1) and the true 50% point. Biases in the which-first task were small (0.2 – 2.5%) and all favoring a report of the standard (short runway) first. Biases were also small in the collision task (0.5 – 1.7%) except for subject MN (9.2%), who often reported “collision” when the comparison disc arrived first.

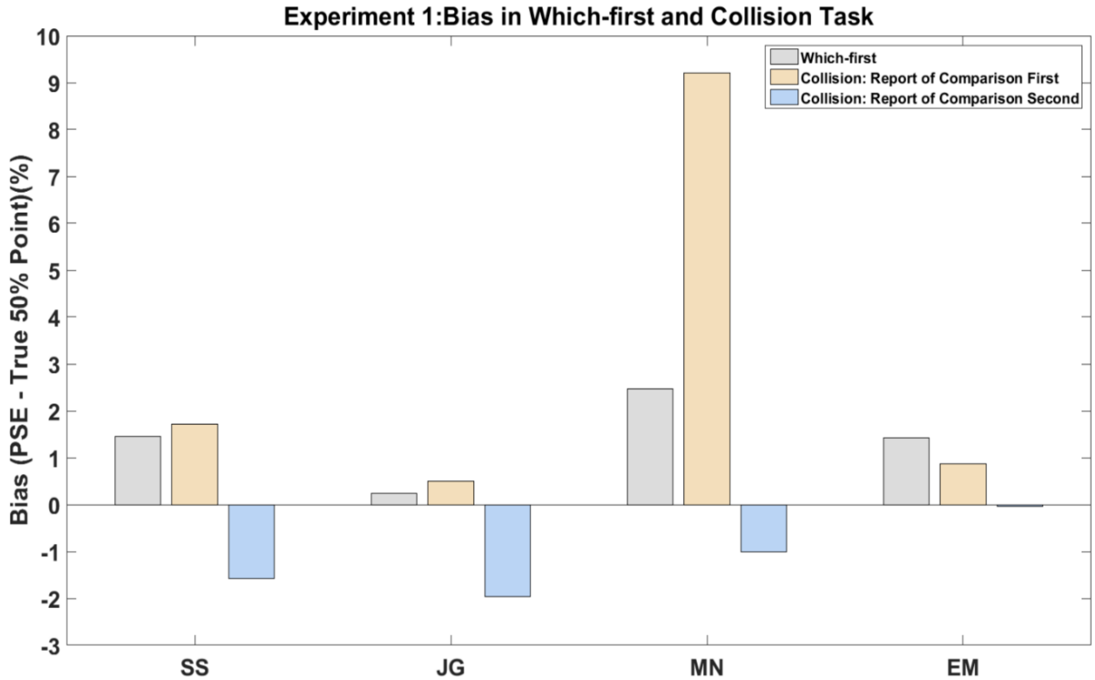


Figure 4. Perceptual biases (%) from the which-first and the collision tasks, four subjects, Experiment 1.

3.1.3. Reaction Time

The added difficulty of the decision in the collision task vs. the which-first task was reflected in the response times. Decision were made earlier for the which-first task. Fig. 5 shows the mean time (+/- SD) between the deadline and the response as a function of the comparison velocity, where “deadline” refers to the time when the first disc reached the meeting point. Larger values indicate earlier responses. All except Subject JG took more to respond in the collision task than in the which-first task.

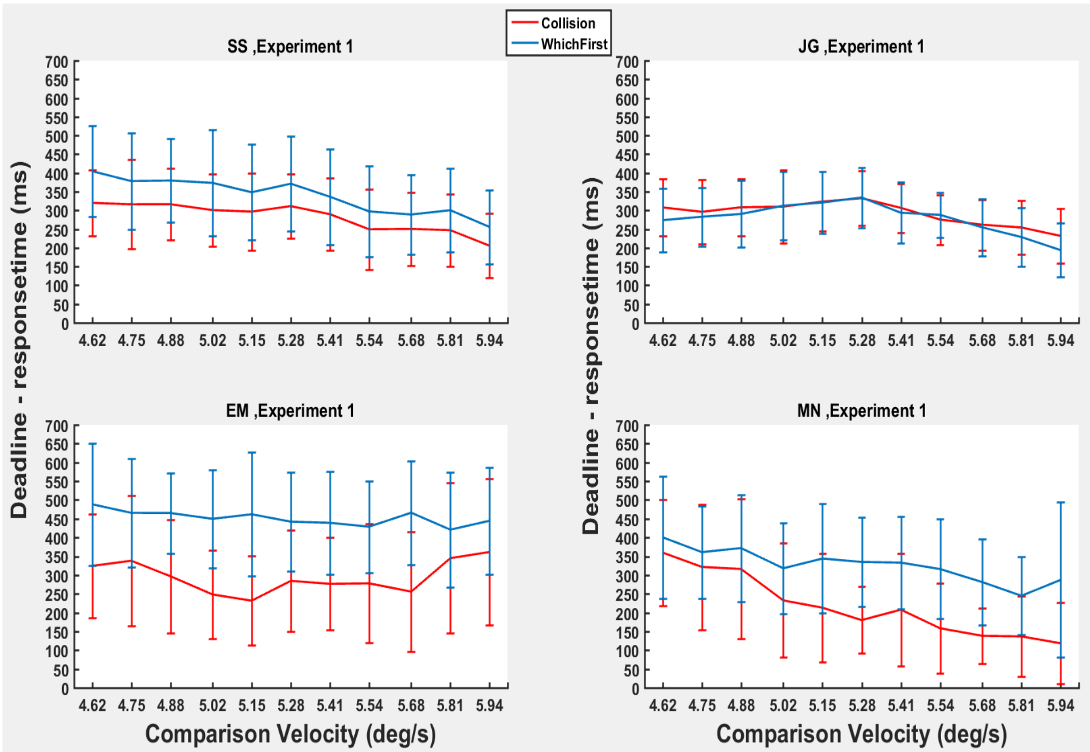


Figure 5. The remaining time relative to the deadline as a function of values of the comparison velocity from the which-first and the collision tasks, four subjects, Experiment 1.

3.1.4. Summary of perceptual performance

In summary, the analysis of the perceptual performance showed that given sufficient exposure to the task, discrimination thresholds were small (<6% of standard velocity) for a task that required judging which of the two discs would arrive first at the meeting point (the which-first task), and for the slightly more difficult task of deciding whether the differences in arrival time would be small enough to result in a collision (the collision task). Responses were made closer to the deadline in the collision task than the which-first task.

3.1.5. Eye movements: Positions

A variety of strategies were available to complete the task, for example, fixating a central location, switching between fixation or pursuit of each disc, or pursuing one disc for the entire time. To distinguish among these strategies, eye positions will be reported first, followed by eye velocities.

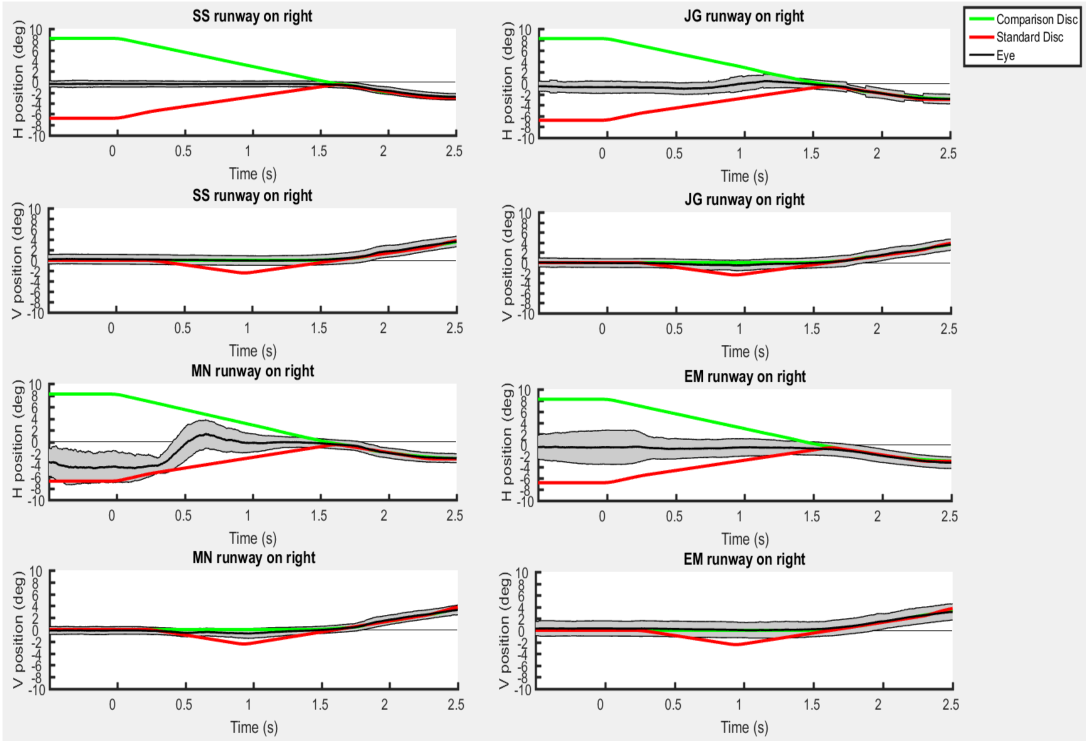
Fig. 6 shows the average horizontal and vertical eye positions (+/- SD), along with average stimulus positions, over time for each subject. Each trace shows position during successive 100-millisecond time periods whose onsets were advanced by 2 milliseconds (Methods section 2.5.2). Time 0 on the x-axis is the onset of motion of the discs. The position of the standard disc (which moved along the short runway and through the traffic diamond) is shown in red and the comparison disc (which moved along the long runway) is shown in green. Eye positions for trials in which the long runway was on the left or the right were averaged together, with positions for trials with the runway on the left rotated before averaging. As a result, performance is depicted as if the long runway (comparison disc) was on the right for all trials (see Methods, section 2.5.2; see also the sketch of the stimulus in Fig. 1). The standard disc moved from left to right along the short runway, moved along two legs of the traffic diamond (down-right; up-right) and reached the meeting point in 1.6 s. The comparison disc moved from right to left along the long runway and reach the meeting point after 1.43 to 1.84 s, depending on its velocity. After reaching the meeting point, the discs completed the final leg of the traffic diamond (up-left) and then moved upward, out the exit.

There were many commonalities and some inter-subject difference in strategies. Consider the which-first strategy (Fig.6A). The mean horizontal eye positions show that two of the subjects, SS and EM, began by fixating near the meeting point (-0.35 deg/s from display center), although EM was more variable.

When the discs reached the meeting point (1.4-1.8 s), mean eye positions began to shift left, consistent with smooth pursuit of the pair discs, as they traveled together to the exit. It is noteworthy that these signs of smooth pursuit occurred well after the decision had been made (Response were recorded 0.3 – 0.4 s before the discs reached the meeting point).

Subject JG's strategy was similar except that the mean eye position was shifted to the right (toward the comparison disc) at 0.8s, about 0.8 s before the discs reached the meeting point. Subject MN's strategy differed from that of the other three in that horizontal eye position began to the left of the meeting point, near the standard disc, and then at about 0.4s shifted to the right, near the comparison disc. MN, like the other three subjects, followed the pair of discs once they reached the meeting point. Strategies were about the same in the collision task (Fig. 6B).

6(A)



6(B)

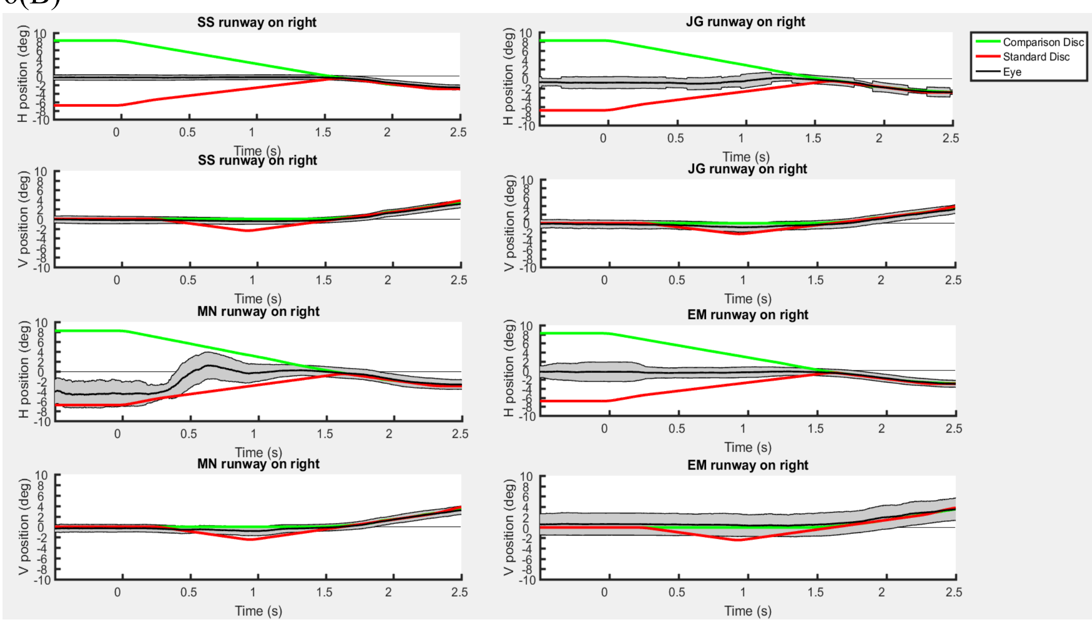


Figure 6. Average eye positions (across trials) over the course of the trial (A: which-first task; B: collision task), four subjects, Experiment 1.

3.1.6. Eye movements: Positions and velocities at different epochs of time

Changes in eye positions over time could be due to saccades or to pursuit. To distinguish these sources of position change, 3-dimensional representations were created (Fig. 7), each showing distribution of both horizontal eye position (x-axis) and horizontal eye velocity (y-axis) at a (0.1s samples) at different times (samples containing saccades or portion of saccades were not included). A broad distribution of eye positions accompanied by non-zero eye velocities suggests episodes in which eye position changed due to pursuit. A broad distribution of eye positions while eye velocity remained near zero suggests eye position changed due to saccades (suggestions about episodes of pursuit will be confirmed in subsequent analyses of eye velocities, section 3.1.6).

Examination of the results in Fig. 7 shows many basic similarities in aspects of the strategies used by each subject, as well as some noteworthy individual differences.

Two subjects, SS (Fig.7A) and EM (Fig.7B) began by fixating near the meeting point with eye velocities near zero. EM showed a broader distribution of eye positions than SS. Increases in eye velocity to the left for SS and EM were apparent at 1.3-1.6 seconds, near the time the discs reached the meeting point and began moving together up and to the left.

JG (Fig.7C), on the other hand, used a somewhat different strategy. Fixation near the meeting point was maintained for a shorter period of time (1- 1.2 s). Then, eye positions shifted to the right, toward the comparison, and velocity increased to the left, suggesting that JG frequently looked toward and pursued leftward motion of the comparison disc prior to the discs reaching the meeting point. Pursuit velocity, however, was only about 40% of the comparison velocity. JG, like the SS and EM, pursued to the left after the pair of discs reached the meeting point.

Subject MN's strategy was different. MN (Fig.7D) began by fixating to the left, nearer the standard disc, with eye velocities tending toward the right, in the direction of motion of the standard disc. At 0.6s eye positions shifted to the right, and velocities to the left, suggesting fixation near and pursuit of the comparison. After the discs reached the meeting point MN's velocities were to the left, similar to the other subjects, and consist with pursuit of the pair of discs as they traveled together along the last leg of the traffic diamond.

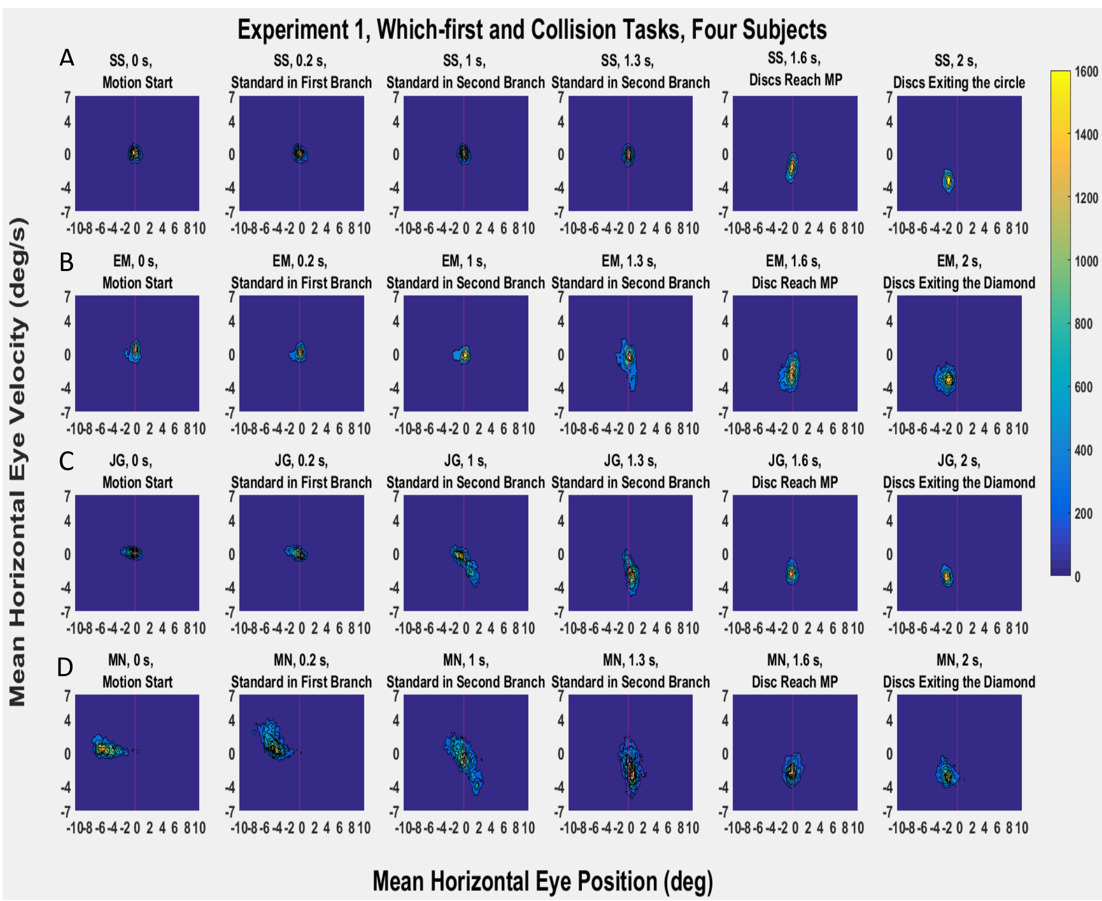


Figure 7. Three-dimensional distributions (top view) representing the horizontal eye position and velocity for different (0.1s) time samples over the course of the trial, four subjects, Experiment 1. Eye samples from the which-first and collision tasks were collapsed into one distribution.

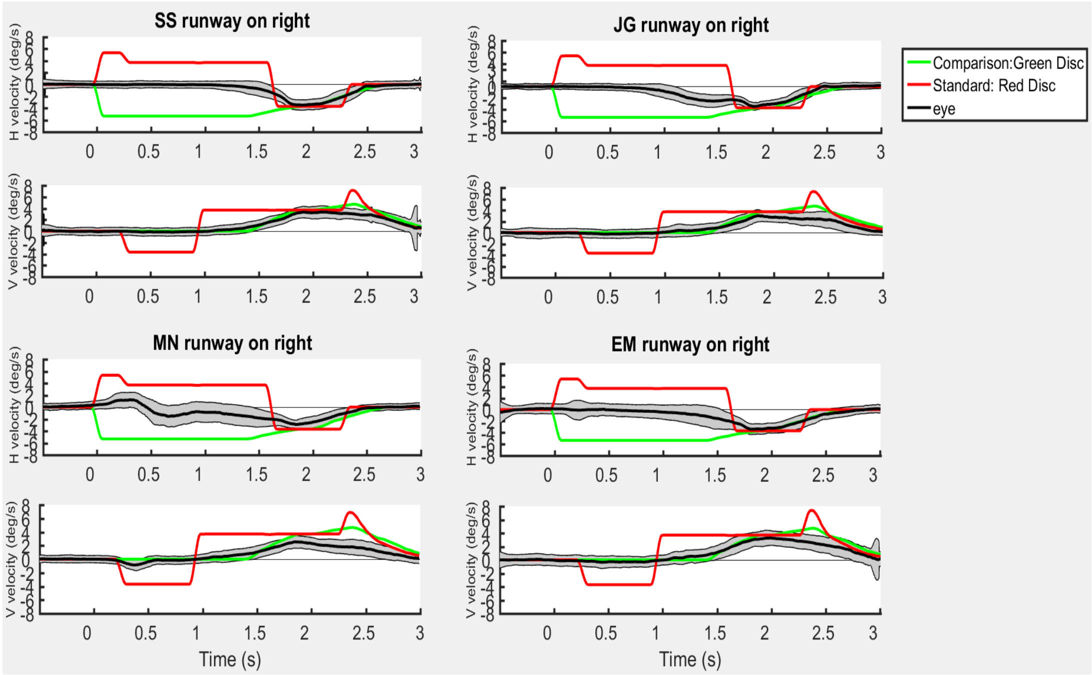
To summarize, all subjects chose strategies that involved decisions that affected both eye velocity and eye position. All also showed evidence for pursuit of the discs by the time they reached the meeting point, after the decision had been recorded. Strategies before the discs reached the meeting point varied, with two subjects (SS and EM) opting to fixate or around the meeting point with little evidence for pursuit, one subject (JG) showing some fixation near and low velocity pursuit of the comparison disc, and the remaining subject (MN) switching fixation between the discs with the switches accompanied by low velocity pursuit of each.

3.1.7. Eye velocities

Eye velocities were analyzed to obtain a more precise look at the pursuit of the discs observed around the time the discs reached the meeting point.

Figure 8 shows the average (+/- SD) horizontal and vertical eye and stimulus velocities over time for each subject. Each trace shows velocity during successive 100-millisecond time periods whose onsets were advanced by 2 milliseconds. In agreement with the analyses described above, JG showed low-velocity horizontal pursuit in the direction of the comparison at about 0.8 s. MN showed low velocity pursuit of the standard and followed the pursuit of the comparison discs. Finally, all four subjects pursued the pair of discs (up to the left) reaching velocity close to disc velocity, when the discs moved up to the left along the final segment of the traffic diamond, with pursuit up to the left often beginning at 0.3 s before the discs reached the meeting point. The pursuit (up-left) that is found prior to the disc reaching the meeting point is likely to reflect anticipatory pursuit of the common motion of the pair of discs rather than pursuit of a selected disc because prior to the meeting point neither disc was moving up and to the left. The comparison was moving to the left and the standard was moving down-right.

8(A)



8(B)

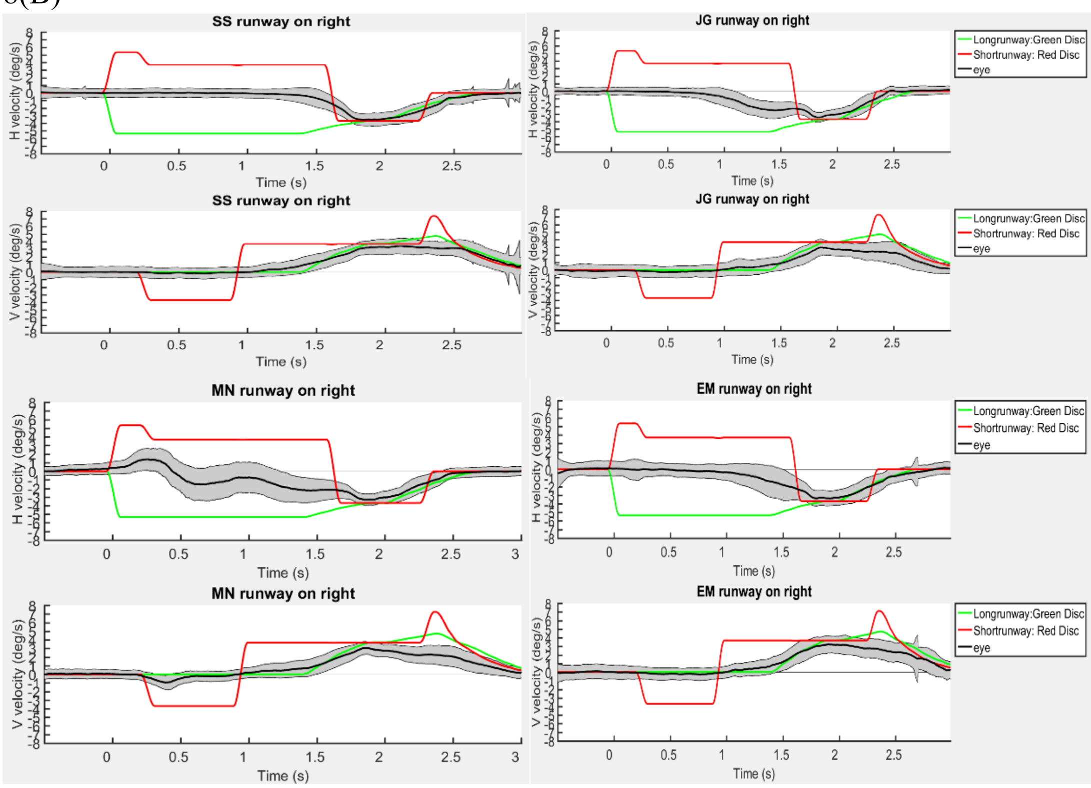


Figure 8. Average eye velocity (across trials) over the course of the trial (A: which-first task; B: collision task), four subjects, Experiment 1.

3.1.8. Fixation vs. divided attention: Evidence for micro-pursuit

The analyses of average eye positions and velocities (Fig. 7) show that the preferred eye movement strategy during at least a portion of the trial was to fixate at or near a central location. Fixation could have been achieved in two ways: (1) using the stationary outline of the display to ensure stable fixation; or (2) dividing attention between the two discs that were moving in opposite directions. These strategies may be distinguished by examining eye velocity as a function of the velocity of the stimuli at different periods of time. A strategy of dividing attention between the discs predicts that the eye velocity would be affected by both velocities. In contrast, a strategy of fixating the stationary display outline predicts that eye velocity would be unaffected by the disc velocities.

Average horizontal eye velocity was examined to determine whether there was an effect of the comparison on fixation. The comparison velocity selected in each trial was from one of 11 different values. Fig. 9 shows mean horizontal eye velocity as a function of the velocity of the comparison stimulus for two representative times, the time at or before the decision (which will be taken as 0.2 s before the time of button press), and the time when the first disc reached the meeting point. Horizontal eye velocity increase as a function of the comparison velocity. This shows that fixation was accompanied by some attention to the comparison disc.

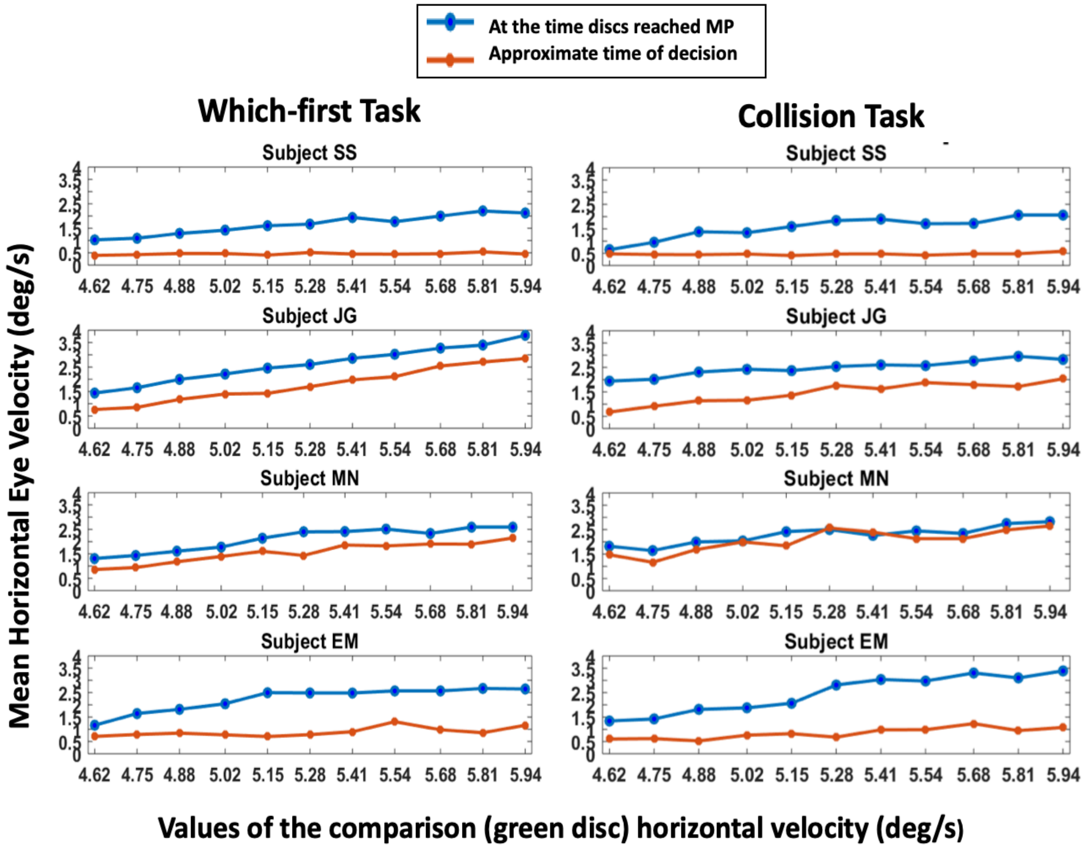


Figure 9. Mean horizontal eye velocity as a function of different values of the Comparison velocity (left column: which-first task; right column: collision task) at two critical time stamps: approximate time of decision (200 ms before button press) and the time the discs reached the meeting point, four subjects, Experiment 1.

What about the attention to the standard disc? During the time the decision was being made, the standard moved purely to the right, then down and to the right (starting about 0.3 s of the motion), then up to the right (starting about 1s of the motion). Average vertical eye velocities were examined for each of the 3 periods of time: when the disc reached the midpoint of the short runway (when the standard motion had no vertical component), the midpoint of the first oblique branch (when the standard moved down and to the left) and when the disc reached the midpoint of the second oblique branch (when the standard moved up and to the left). Fig. 10 shows that the mean vertical eye velocities varied as a function of the vertical component of the standard velocity.

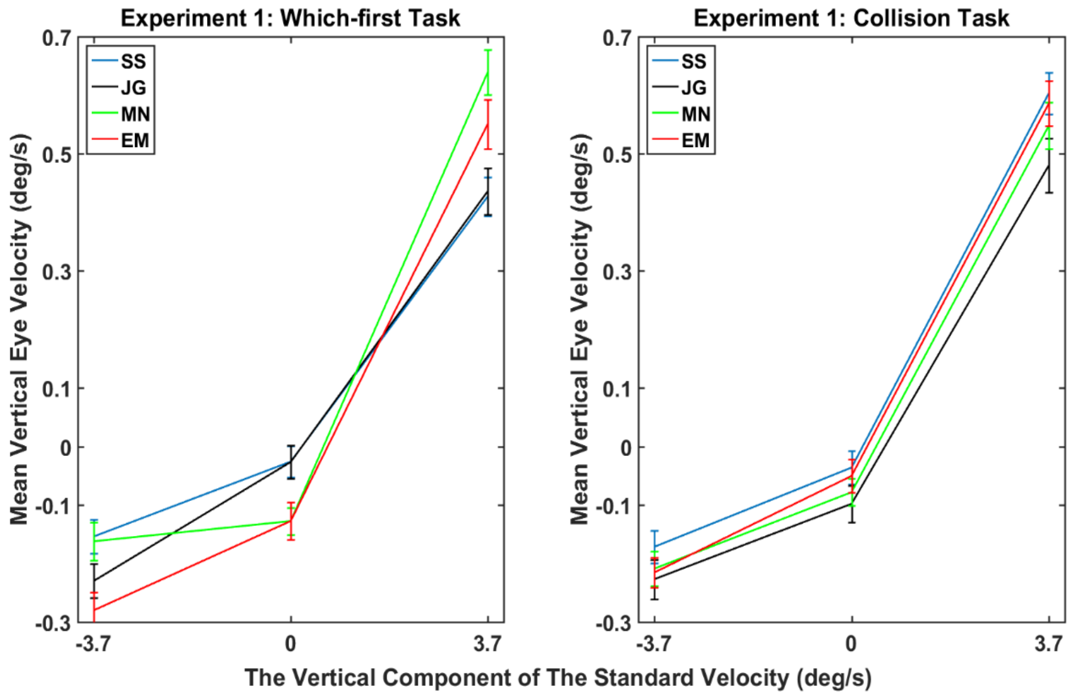


Figure 10. Mean vertical eye velocity as a function of three vertical components of the Standard velocity in the which-first and the collision tasks, four subjects, Experiment 1.

These analyses of low velocity micro-pursuit provide support for the view that attention was allocated to both the comparison and the standard discs during the time the decision was being made.

3.1.9. Summary of eye movements

To summarize, the preferred eye strategy in Experiment 1 can be characterized as fixating near the meeting point before the decision was made (Subject SS and EM), with a small bias toward the comparison (Subject JG), and some switches from the standard to the comparison (Subject MN). During this time all subjects showed an influence of both discs on eye velocity (micro-pursuit), suggesting attention was divided between the discs moving in opposite directions. The division of attention was further supported by finding smooth pursuit of the pair of discs along the final leg of the traffic diamond. To compare the effective of these strategies, Experiment 2 tested the same tasks on the same subjects with the strategy determined by instructions.

3.2. Experiment 2: Fixate vs. Switch

3.2.1. Methods

The goal of Experiment 2 was to examine whether the preferred eye strategy in Experiment 1 was indeed the better strategy to use in the two perceptual tasks. Methods were the same as for Experiment 1 except for the instructions. Instructions were tested in separate blocks of 80 trials. The fixate instruction asked subjects to fixate the estimated meeting point, which people learned from seeing the trials from Experiment 1. The switch instruction required subjects to switch fixations between two discs at least once after the motion onset of the discs. The instructions only applied to the time period when the decision was being made.

3.2.2. Perceptual performance

Performance of all four subjects showed precise perceptual discrimination for both tasks (which-first and collision) and both eye strategies (fixate and switch), with Weber fractions ranging from 2 – 5%. Three out of four subjects showed better discrimination with the fixate than the switch eye strategy in the which-first task (Fig. 11). Subject JG, in contrast, showed better discrimination with the switch eye strategy than the fixate strategy. Results were similar in the collision task (Fig. 12). Across all four subjects the average Weber fraction for the which-first task was 2.94% (SD = 0.23) with the fixate instruction, and 4.14% (SD = 0.34) with the switch instruction.

The average Weber fraction for the collision task was 3.77% (SD = 0.27) with the fixate instruction and 4.14% (SD = 0.31) with the switch instruction when responses were grouped as comparison disc first vs. collision+comparison second, 3.09% (SD = 0.23) with the fixate strategy and 3.95% (SD = 0.28) with the switch strategy for when the responses were grouped as comparison first+collision vs. comparison second.

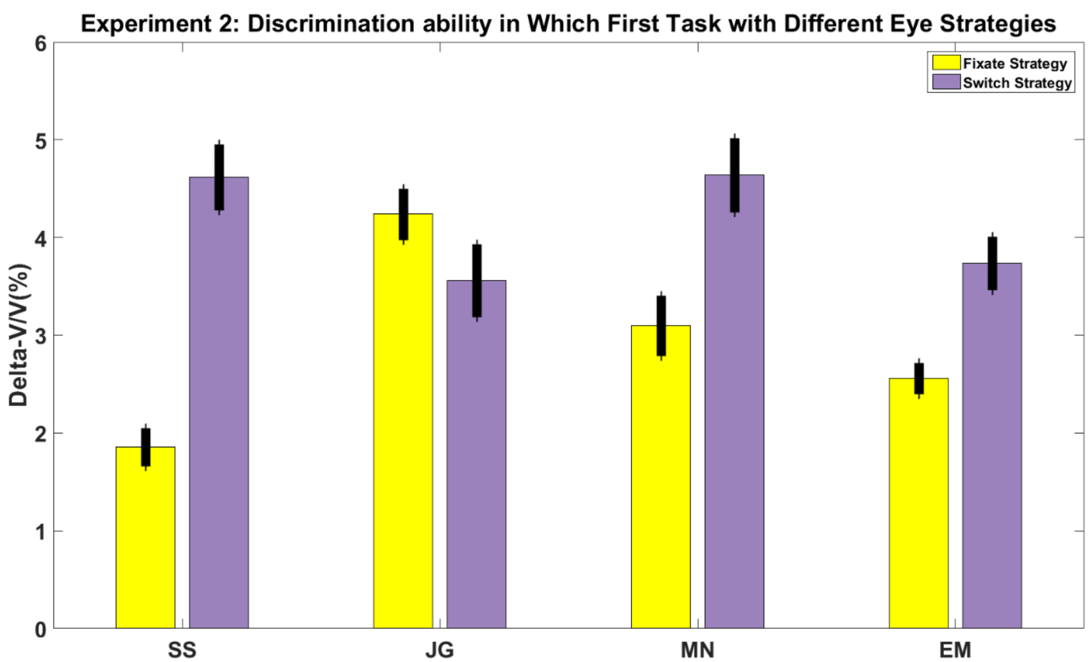


Figure 11. Perceptual discriminations assessed by Weber fractions from the which-first task with the fixate and the switch eye strategies, four subjects, Experiment 2.

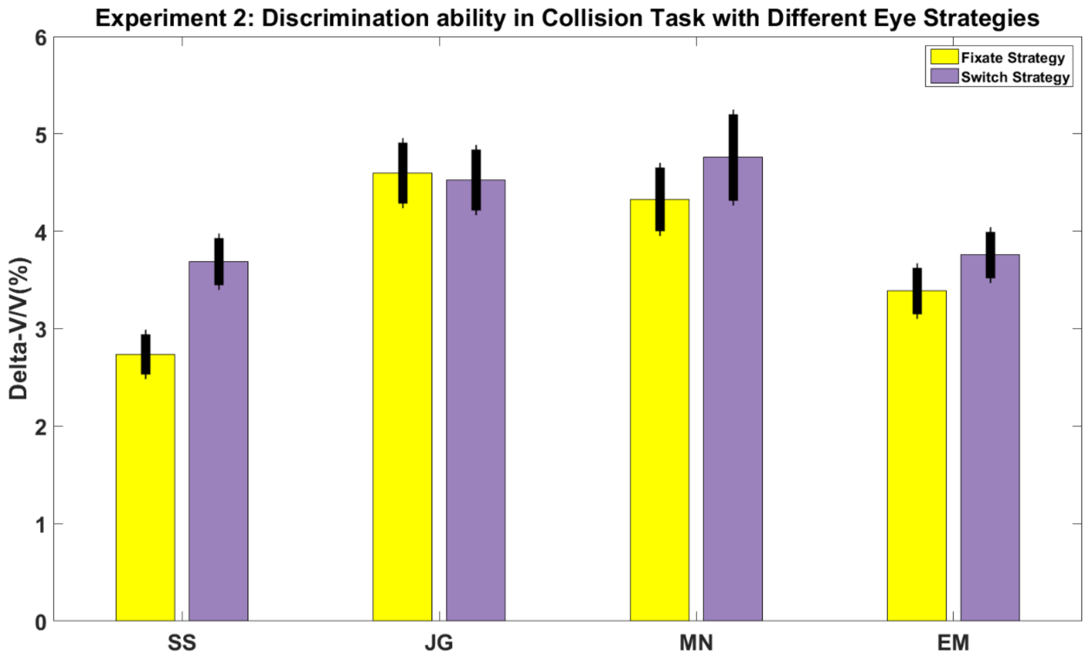


Figure 12. Perceptual discriminations assessed by Weber fractions from the collision task with the fixate and the switch eye strategies, four subjects, Experiment 2.

3.2.3. Reaction Time

Mean reaction times were separated by the tasks and the eye strategies. As shown in Fig. 13, all subjects responded earlier with the fixate strategy than with the switch strategy for the which-first task. Results were similar for the collision task except that MN responded faster with the switch strategy than with the fixate strategy.

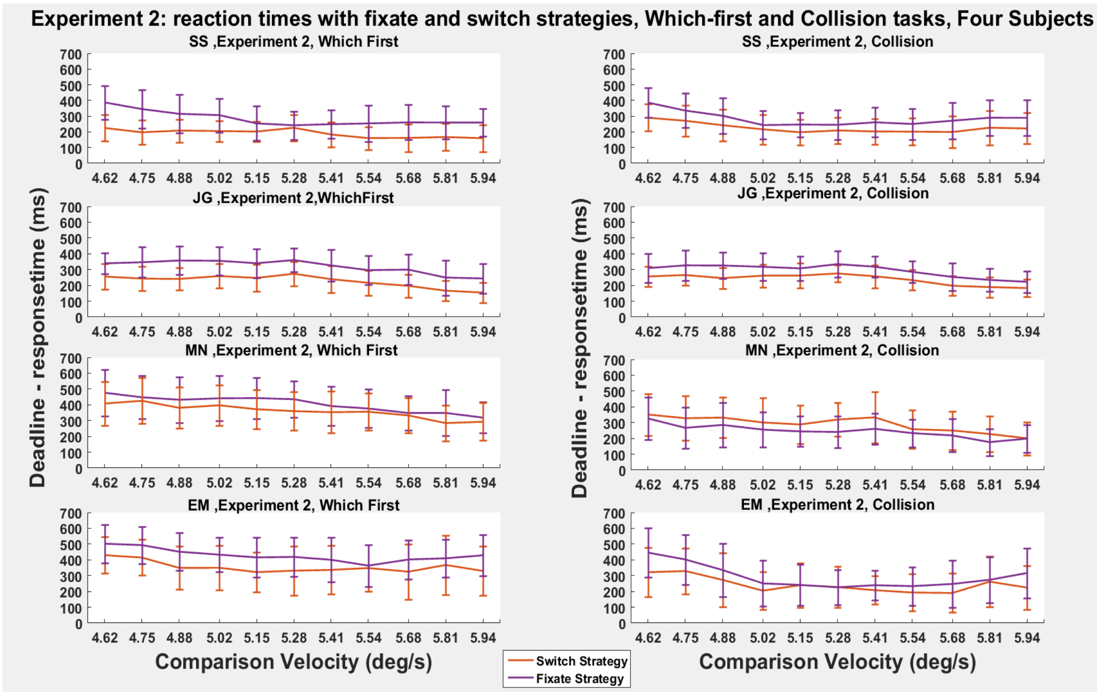


Figure 13. The remaining time relative to the deadline under the fixate and the switch eye strategies as a function of values of the Comparison velocity, in the which-first (left column) and the collision (right column) tasks, four subjects, Experiment 2.

3.2.4. Summary of perceptual performance under different eye strategies

To summarize, the analysis of perceptual performance from Experiment 2 indicates that the fixate strategy led to better perceptual discrimination in three of four subjects when judging the relative motion of two discs heading toward the same meeting point. Responses were also made earlier with the fixate strategy than the switch strategy.

3.2.5. Eye movements: Positions and velocities at different epochs of time

Three-dimensional representations showing the distributions of both horizontal eye position and velocity confirms that all four subjects followed the eye strategy instructions, with one interesting variation. When the instruction was to fixate at the meeting point until decision was made, all four subjects showed eye positions around at the meeting point with eye velocities near zero for 1.4 s of the motion (Fig. 14).

Subject SS, MN and EM began to exhibit pursuit (indicated by increases in eye velocity to the left) on average 0.3 s prior to discs reaching the meeting point, similar to Experiment 1. Then, the eye moved up and to the left, indicating the pursuit of the pair of discs as they traveled together along the last oblique branch of the traffic diamond. The variation was observed for JG. JG fixated near the meeting point with no increases in eye velocity even after the discs reached the meeting point at 1.6 s. This suggests that one subject attempted to suppress all pursuit, attended to the stationary outline of the display rather than dividing attention between the discs. This might explain JG's poorer perceptual performance with the fixate instruction than with the switch instruction (Fig. 11 and 12).

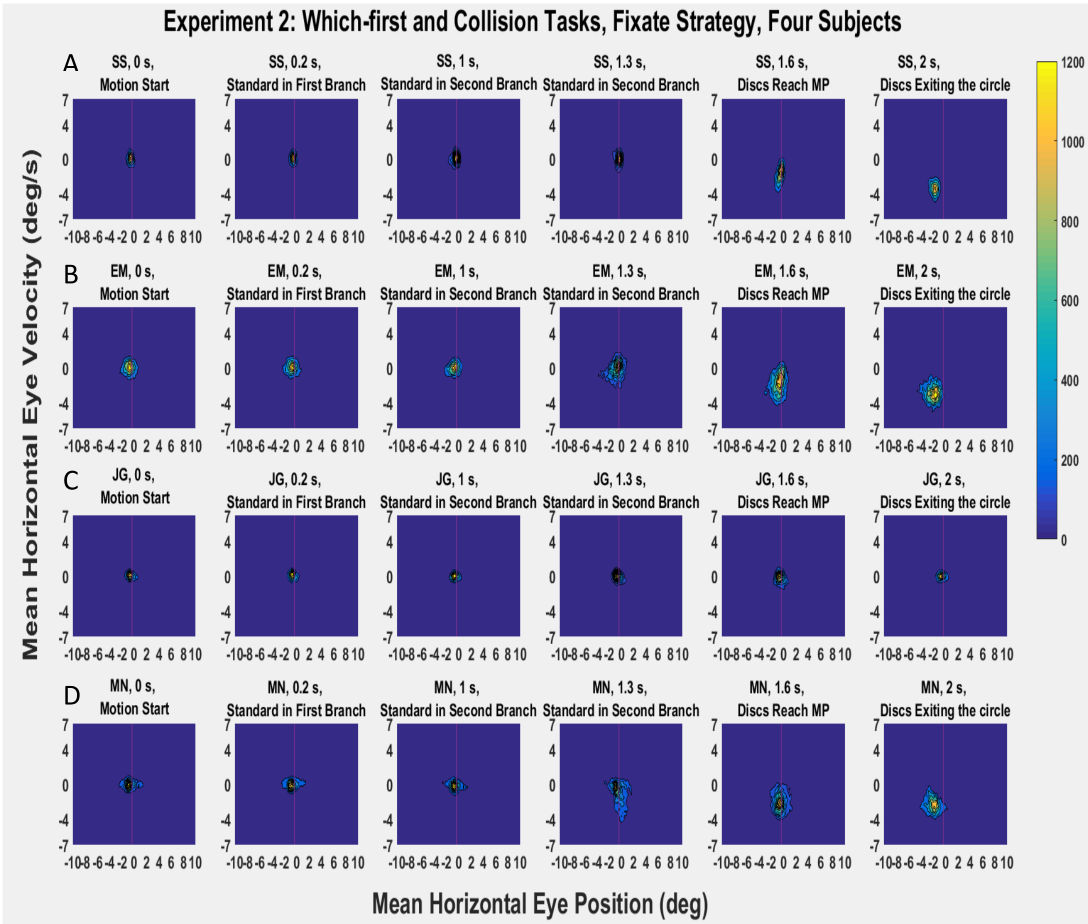


Figure 14. Three-dimensional distributions (top view) representing the horizontal eye position and velocity for different (0.1s) time samples over the course of the trial under the fixate instruction, four subjects, Experiment 1. Eye samples from the which-first and collision tasks were collapsed into one distribution.

All subjects carried out the switch strategy successfully, dividing time between the discs. Fixation of either disc was typically accompanied by pursuit at about the same velocity as the disc velocity (Fig 15). After the discs reached the meeting point at 1.6 s, all four subjects pursued the discs exiting the traffic diamond. A more detailed analysis of the switch strategy is beyond the scope of the strategy.

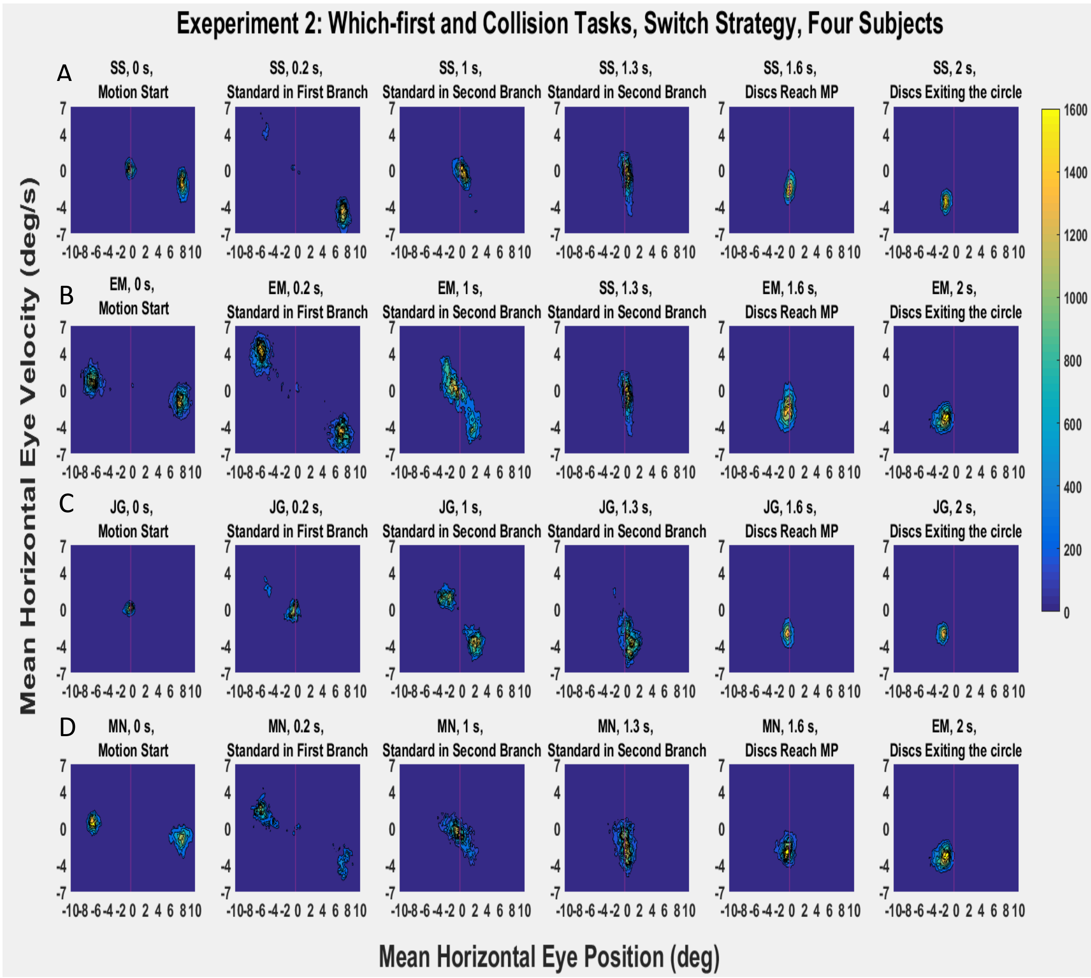


Figure 15. Three-dimensional distributions (top view) representing the horizontal eye position and velocity for different (0.1s) time samples over the course of the trial under the switch instruction, four subjects, Experiment 1. Eye samples from the which-first and collision tasks were collapsed into one distribution.

3.2.6. Fixation instruction: diminished micro-pursuit

Mean horizontal eye velocity under the fixation instruction was compared with the horizontal velocity of the comparison disc to see whether micro-pursuit occurred during the fixation at the approximated time of decision and at the time when the first disc reached the meeting point. Surprisingly, the eye velocity of all four subjects did not vary as a function of the comparison velocity at the approximate time of decision for both which-first and collision tasks, indicating the micro-pursuit found under the free-viewing strategy (Experiment 1) was suppressed when subjects were told to fixate near the meeting point (Fig.16). One subject, JG, also suppressed the pursuit at the time when the discs reached the meeting point, which confirms the results on JG determined from the three-dimensional representations of the eye position and velocity (Fig. 14 and Fig 15). The pattern of results suggests JG may have reduced attention to the moving discs during the judgment, under fixation instruction.

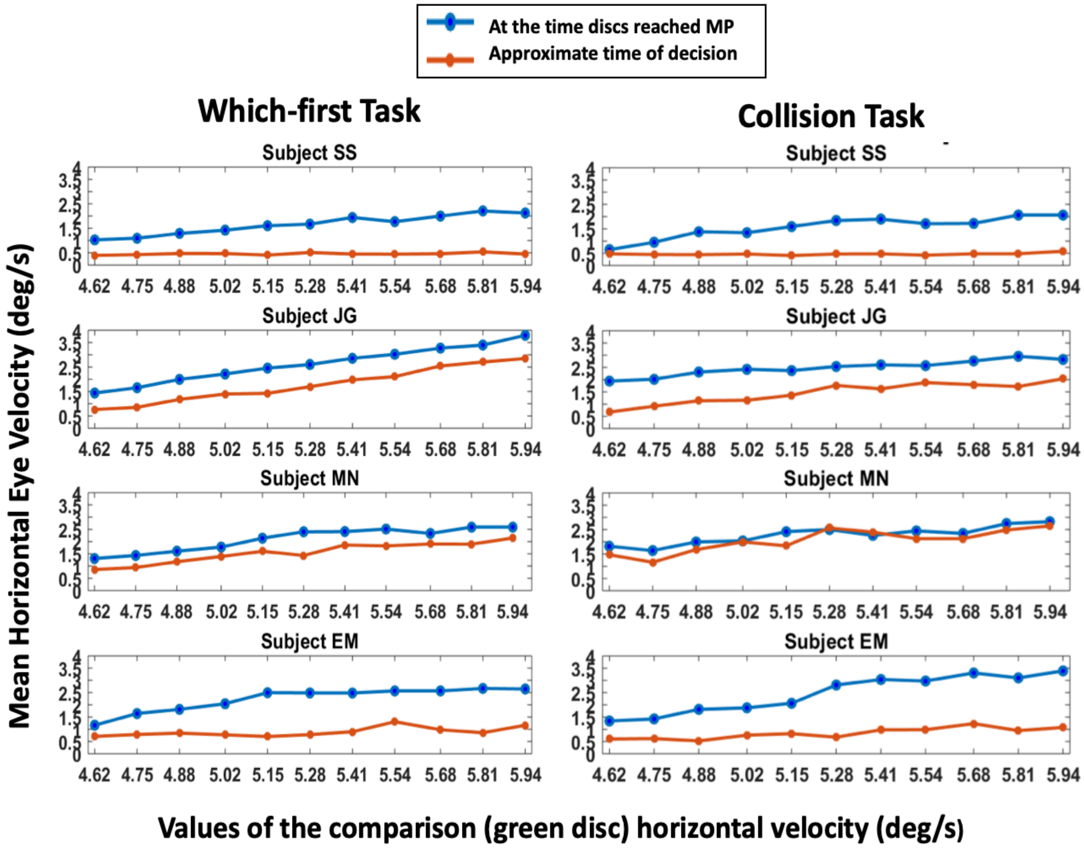


Figure 16. Mean horizontal eye velocity as a function of different values of the Comparison velocity (left column: which-first task; right column: collision task) under the fixate instruction at two critical time stamps: approximate time of decision (200 ms before button press) and the time the discs reached the meeting point, four subjects, Experiment 2.

3.2.7. Summary

To summarize, all subjects showed eye movements consistent with the assigned strategy in Experiment 2. Perceptual performance was somewhat better with the fixate than the switch strategy for three of four subjects (except for JG). Response were made earlier with the fixate than the switch strategy for both which-first and collision tasks (except for MN in the collision task). There was little micro-pursuit at the time of the decision under the fixate strategy, suggesting reduced attention to the moving discs. However, the reduced attention did not impair the perceptual performance.

4. Discussion

4.1. Overall summary of Experiment 1 and 2

The current study examined perceptual performance and eye strategies in tasks modeled after judgements made in traffic circles. Subjects judged the relative motion of two discs moving toward a common meeting point under either a free-viewing eye strategy (Experiment 1) or an assigned eye strategy (Experiment 2: fixate near the meeting point or switch between the discs).

The perceptual task required judging which disc would arrive first (2AFC) or whether one or the other would arrive first or the discs would collide (overlap) at the meeting point (3AFC). Perceptual performance assessed by Weber fractions was excellent when judging the relative motion of discs in both tasks. In Experiment 1 (free-viewing) the preferred eye strategy was to look near the meeting point rather than switch between the discs. The eye, however, was not perfectly stable. Eye velocity varied as a function of both standard and comparison discs velocities, with velocities far less than the velocity of the stimuli (30-50% of target velocity). Because of the low eye velocities, I termed this phenomenon “micropursuit”. Given the well-established relationships between pursuit eye movements and attention (Khurana and Kowler, 1987; Suoto and Kerzel, 2008), the occurrence of micropursuit provides evidence that subjects were attending to both targets during the judgments. The results of Experiment 2, where strategies were assigned, showed that looking near the meeting point led to slightly better performance than switching. However, the fixate instruction in Experiment 2 suppressed the micropursuit found under the free-viewing strategy in Experiment 1, without a cost in perceptual performance. This suggests that paying somewhat less attention to the moving discs, or reducing the micropursuit, may not have been harmful to perceptual performance.

4.2. Perceptual performance

The current study used two perceptual tasks termed which-first (2AFC) and collision (3AFC). The which-first task required subjects to judge which disc would reach the meeting point first and the collision task required subjects to judge (1) whether the two discs would collide at the meeting point, and (2) if not, which disc would reach the meeting point first. All subjects showed precise discrimination (Weber fractions < 6%, similar to what is observed in velocity discrimination experiments; McKee, 1981) in both the which-first and collision tasks in Experiment 1. However, the reaction time were longer in the collision task than the which-first task, reflecting the added difficulty of the 3AFC judgments (requiring two decision criteria), or the added difficulty of judging how much faster one target moves relative to the other.

Perceptual performance was further examined with different eye movement instructions in Experiment 2: fixate near the meeting point (fixate instruction) or switch between the two moving discs (switch instruction). Perceptual discrimination was better with the fixate instruction in three of four subjects (except for JG) and the reaction time was slightly shorter with the fixate instruction, suggesting that fixate strategy in Experiment 2 might have been better than the switch strategy.

There are several possible factors that could have contributed to the slightly poorer performance under the switch strategy. First, each switch improves the resolution of the fixated target at the expense of the eccentric target (Fehd and Seiffert, 2010). Prior studies linked reductions in motion discrimination to increased retinal eccentricities, suggesting even small increases in eccentricities could be harmful (McKee and Nakayama, 1984; Poletti, Listorti and Rucci, 2013). Also evidence showed that perception is suppressed to some degree during saccades (Burr, Morgan and Morrone, 1999). For all these reasons, when the primary focus of the task was to judge the relative motion of the two targets, it might be better to have an intermediate retinal location for both targets at all times, without interruption by saccades. However, quantifying the benefit of a central-looking strategy solely based on eccentricity can be hard. Since the eye was pursuing the target being fixated during the switch task, there were also changes in the retinal speed of eccentric target (McKee and Welch, 1989). In addition, the retinal speeds of the targets were different due to this pursuit. So it is not a simple matter to quantify effects of eccentricity because both target position and velocity were dynamically changing.

Perceptual performance could also be deteriorated in the switch task due to attention. Prior to the saccade of switch, attention will shift to the selected target (Kowler et. al., 1995; Zhao et.al., 2012). This shift will affect the perceptibility of the eccentric target, especially when subjects are trying to judge multiple objects at once (Huang and Dobkins, 2004). Moreover, managing the switches between moving targets could be complicated because deciding when to switch requires management of the task (Rubinstein and Kowler, 2018). In current study, the number of switches that can be made within the limited amount of time and how long the eye needs to pursue the fixated target to gather enough motion information before making the next switch need to be taken into account. This means, management of switches require efforts and decision-making to balance the number of switches and the length of pursuit of each target to obtain a good performance.

4.3. The role of micropursuit

Micropursuit was first revealed in current study. Researchers in the past emphasized static displays when studying the utility of eye movements. Studies of tasks such as the virtual needle threading, virtual maze navigation, or the reaching either did not find fast enough eye velocities to be called pursuit (Ko, Poletti and Rucci, 2010), or did not analyze how eye velocity might have varied as a function of the momentary velocity of the target (Kowler et. al., 2014; Johansson et. al., 2001). With a dynamic display, where two discs moved in opposite directions to a common meeting point, the current study (Experiment 1) found the sign of micropursuit when the eye was fixating near the meeting point.

The role of micropursuit is still unclear. In the current study, perceptual performance was good with (Experiment 1) or without (Experiment 2) micropursuit. However, there are other factors that could offset the effect of micropursuit. First, perceptual performance of all four subjects had reached near asymptotic levels (Fig. 3) before Experiment 2. This means in Experiment 2 with the same stimuli (same velocity and trajectory) and perceptual tasks, subjects were all well-trained so that they did not necessarily need to rely on as much attention to achieve good performance. Or, they may have gotten better at maintaining fixation while attending moving targets. Thus, perceptual performance was not harmed despite using a fixate eye strategy that did not incorporate micropursuit. For example, in Experiment 2 under the fixate instruction, Subject JG chose to maintain fixation near the meeting point even after the discs reached the meeting point, rather than pursuing the pair of discs, suggesting that JG was attending more to the meeting point on the static "diamond" display and less to the moving targets, than the other three subjects. This might account for why JG's perceptual performance was similar across the fixate and switch strategies in Experiment 2.

Future studies should explore the role of micropursuit in different perceptual tasks involving multiple moving targets. For example, using stimuli at near threshold contrast may increase the importance of attention (Dosher and Lu, 2000; Souto and Kerzel, 2011; Spering and Carrasco, 2012; Zhao et al., 2012), thereby encouraging micropursuit.

4.4. The link between attention and micropursuit

A link between attention and pursuit has been reported in the past by dual-task studies showing that attention is allocated to the pursuit target (Khurana and Kowler, 1987; Suoto and Kerzel, 2008). The evidence for micropursuit, and the pursuit of the disc pair after they reached the meeting point found in the current study provide overt indicators that attention was divided between the moving targets. One would ask how we knew it was attention, not just the global motion of the two discs, driving micropursuit. This question can be addressed by scrutinizing the design of the two experiments. Experiment 1 and 2 used the same stimuli and perceptual tasks, but different eye movement instructions: free-viewing in Experiment 1 and instructions to fixate near the meeting point or switch between discs in Experiment 2. The micro-pursuit found under the free-viewing instruction was diminished in Experiment 2 under the fixate instruction, despite that fact that Experiment 2 used same stimuli and perceptual tasks as Experiment 1. Thus, the suppression of micropursuit in Experiment 2 under the fixate instruction should be attributed to the change in eye movement strategy, suggesting that the diminished micropursuit is more likely caused by the shift of some attention from the moving targets to the static display.

4.5. Value of smooth pursuit

Many prior studies examined eye strategies with static displays by only looking at the eye positions. This might be sufficient if the eye strategies were used in stationary displays. When the visual task involves moving objects, however, the eye strategies involve both the choice of eye position and the choice of whether or not to pursue. When studying eye strategies in dynamic environments, it is necessary to analyze both eye position and velocity. For example, in the multiple object tracking experiment (Fehd and Seffert, 2010) requiring using attention to track several moving targets in the presence of distractors, subjects were found to favor a central-looking strategy among the moving targets than a target-looking strategy regardless of the object speed and size. The reluctance to switch between targets and better tracking performance associated with the central-looking strategy suggest that there might be some merits of the central fixation strategy when attending to multiple objects. To reveal the usefulness of the central fixation strategy in a multiple object tracking task, one could analyze eye position with eye velocity to provide evidence that center-looking strategy might facilitate better allocation of attention on all moving targets.

4.6. Conclusions

People are able to judge the relative motions of targets precisely in either 2AFC or 3AFC tasks. In agreement with prior studies of tasks other than manual interception, the preferred and better strategy is to fixate near a central location. However, unlike prior claims, the velocity of the eye depended on the velocities of the targets, suggesting that attention was divided between targets while a central fixation location was maintained. The small changes of eye velocity are termed micropursuit.

The present results showed that understanding eye strategies in dynamic environments requires analyzing eye velocity, and not just eye position. Without analyzing both we could not infer the distribution of attention under the fixate strategy. The results contribute to the view that fixating near a central location among moving targets allows dividing attention among all moving targets. Arguing further from this conclusion, we could infer that one reason why pursuit maybe helpful in some tasks and not others, the questions posed at the beginning of the paper, might involve the distribution of attention that is best for a given visual task.

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