

Published in final edited form as:

J Vis. ; 10(2): 22.1–2212. doi:10.1167/10.2.22.

Amplitudes and Directions of Individual Saccades Can Be Adjusted by Corollary Discharge

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Abstract

There is strong evidence that the brain can use an internally generated copy of motor commands, a corollary discharge, to guide rapid sequential saccades. Much of this evidence comes from the double-step paradigm: after two briefly flashed visual targets have disappeared, the subject makes two sequential saccades to the targets. Recent studies on the monkey revealed that amplitude variations of the first saccade led to compensation by the second saccade, mediated by a corollary discharge. Here, we investigated whether such saccade-by-saccade compensation occurs in humans, and we made three new observations. First, we replicated previous findings from the monkey: following first saccade amplitude variations, the direction of the second saccade compensated for the error. Second, the change in direction of the second saccade followed variations in vertical as well as horizontal first saccades although the compensation following horizontal saccades was significantly more accurate. Third, by examining oblique saccades, we are able to show that first saccade variations are compensated by adjustment in saccade amplitude in addition to direction. Together, our results demonstrate that it is likely that a corollary discharge in humans can be used to adjust both saccade direction and amplitude following variations in individual saccades.

Keywords

Corollary Discharge; Saccadic Eye Movement; Movement Vector

INTRODUCTION

Visual input is continuously disrupted by the rapid or saccadic eye movements we make to sample the surrounding environment. Experiments in the frontal cortex of monkeys suggest that these self-generated displacements are distinguished from those occurring naturally in visual space by the use of an internally generated copy of the motor command, a corollary discharge (CD, Duhamel, Goldberg, Fitzgibbon, Sirigu & Grafman, 1992, Sommer & Wurtz, 2006, Sommer & Wurtz, 2008, Umeno & Goldberg, 1997). In addition to providing this stability, the CD can also be used to guide saccades in cases where visual input is not available or is inadequate.

This guidance of saccades based on an internally generated CD has been studied in both monkeys and humans using the double-step task introduced by Hallett & Lightstone (1976). In this task the subject makes a saccade that depends on deriving the current position of the eye from the CD of the previous saccade. For example, in the schematic in Figure 1A, the subject makes a horizontal saccade from the fixation point (FP) to the horizontal target (T1)

and then from that position makes a vertical saccade to the vertical target (T2). The subject is in the dark and the targets are flashed rapidly so that by the time the first saccade occurs no visual cues are available. The first saccade can obviously be made from the memory of the target location. The second saccade, however, can only be accurately made if the position of the eye after the first saccade is known. If there is no information that eye position has changed after the first saccade, the subject would make a diagonal saccade corresponding to the location of the second target with respect to the original starting fixation position (Figure 1A, 2nd saccade without CD). If the position of the first saccade can be derived from some extra-retinal input, then subjects have the information to make the saccade to the target accurately (Figure 1A, 2nd saccade with CD), which Hallett & Lightstone (1976) showed they could do.

In addition to a CD formed as the first saccade is generated, the other extraretinal signal available to correctly direct the second saccade is proprioception from the eye muscles. Experiments in monkey, which interrupted the nerves carrying the proprioceptive signals to the brain, have shown that the monkey is still able to accurately perform the double-step task in the absence of proprioception (Guthrie, Porter & Sparks, 1983). Subsequent experiments that also interrupted the proprioceptive input concluded that proprioception is likely to be used for long-term adjustments, but is not important for individual saccades (Lewis, Zee, Hayman & Tamargo, 2001). This and other evidence (Wurtz, 2008) indicates that the extra-retinal signal used by the second saccade in our double-step experiments probably is not proprioception. In the present studies, therefore, we will refer to the extra-retinal signal as a CD.

Recent experiments in monkeys have also shown that interrupting a pathway from the superior colliculus to frontal cortex disrupts the second saccade of the double-step task in ways consistent with the pathway carrying a CD from brainstem to cortex (Sommer & Wurtz, 2002, Sommer & Wurtz, 2004b). In the course of these experiments it became clear that the normal monkeys showed variations in the amplitude of the first horizontal saccade (depicted by the red ellipse in Figure 1B). Some first saccades undershot while others overshot the target. When they did so, the direction of the second vertical saccade compensated for these variations as illustrated by the gray arrows in Figure 1B. This compensation is consistent with the monkey using the CD of the first saccade to determine the direction of the saccade required to reach the second target. This CD dependence of the second saccade for its direction was verified by interrupting the CD pathway: the compensation was significantly diminished.

In the present double-step experiments we recorded saccades in humans to determine the extent to which variations in the amplitude of the first saccade were compensated by changes in the second saccade. First, we verified that variations in the amplitude of a horizontal first saccade are compensated by changes in direction of the vertical second saccade as is the case in monkeys. Second, we investigated whether the compensation in second saccade direction is evident with vertical first saccades, a point not explored in the monkey. Differences in how the horizontal and vertical saccadic eye movements are generated (Leigh & Zee, 2006) raises the possibility that there might be differences between the two movement directions, but we find compensations for both directions, although they are more accurate following horizontal first saccades. Third, we determined whether the second saccade compensates by changes in its amplitude as well as in its direction. We did this by examining oblique saccades, and we are able to show adjustment in the amplitude of the second eye movement. Our results indicate that in the absence of visual guidance, humans as well monkeys, can use an extra-retinal signal, which we take to be a CD, to adjust both saccade direction and amplitude on a saccade-by-saccade basis.

METHODS

We recorded the eye movements of five healthy human subjects between the ages of 30 and 57 who had normal vision with correction. Three subjects were naïve as to the aim of the study. Experimental protocols were approved by the Institutional Review Committee concerned with the use of human subjects, and informed consent was obtained from each participant.

The horizontal and vertical positions of the right eye were recorded with a scleral search coil (Collewijn, van der Mark & Jansen, 1975) in a magnetic field (Robinson, 1963), with sampling at 1000 Hz. Subjects were seated in a dark room on a stationary chair in front of a tangent screen (183 cm by 138 cm in size) located 100 cm in front of the subject and the head was fixed with a chin and forehead rest. A red laser back-projected targets onto the screen. The system was calibrated prior to data acquisition by having subjects fixate the eight target locations used in the experiment. A PC running real-time experimental control software (REX, Hays, Richmond, & Optican, 1982) controlled stimulus presentation and storage of eye movement data.

During the double-step task (Hallett & Lightstone, 1976), subjects were instructed to make two saccadic eye movements to two sequentially flashed targets. Targets were presented in different sequences and locations which are grouped into the following three conditions.

Condition 1: Horizontal-Vertical Saccade Sequence

In this condition the first target was a horizontal diffuse strip centered at 10° either to the right or left of fixation ($\pm 10^\circ, 0^\circ$). We used a diffuse target strip in order to maximize first saccade endpoint variability and have more trials on which to evaluate adjustments in the second saccade direction. This target was followed by a second target (a spot) flashed 10° vertically above or below the strip. Starting from fixation, there were four possible target sequences, only one of which ($0^\circ, 0^\circ$ to $10^\circ, 0^\circ$ to $10^\circ, 10^\circ$) is depicted in Figure 2, left.

Condition 2: Vertical-Horizontal Saccade Sequence

This condition was a 90° rotation of Condition 1. The first target was a vertical strip centered 10° either above or below fixation ($0^\circ, \pm 10^\circ$). This target was followed by a second target (a spot) flashed 10° horizontally to the left or right of the strip. Starting from fixation, there were four possible target sequences, only one of which ($0^\circ, 0^\circ$ to $0^\circ, 10^\circ$ to $10^\circ, 10^\circ$) is depicted in Figure 2, middle.

Condition 3: Oblique Saccade Sequence

This condition was a 45° rotation of Condition 1. Unlike condition 1 and 2, the first target was a spot (rather than a strip) located diagonally from fixation (either at $-7.1^\circ, 7.1^\circ$ or $7.1^\circ, -7.1^\circ$). This target was followed by a spot located orthogonal and 10° away from the first. Similar to the other two conditions, there were four possible target sequences starting from fixation, one of which ($0^\circ, 0^\circ$ to $-7.1^\circ, 7.1^\circ$ to $0^\circ, 14.1^\circ$) is depicted in Figure 2, right.

For all three conditions each trial began with a variable period (1200–1800ms) of fixation at the center target. Following this, the center target was extinguished and two peripheral targets appeared in succession: either a diffuse target strip (4° by 2° , 1.0 cd/m^2) or a spot (0.3° in size, 3.5 cd/m^2). The first target appeared for 120 ms and the second for 50 ms.

Each subject completed three blocks (one for each target condition) of approximately 200 trials (50 trials for each of the four sequences). Although the target condition was kept constant throughout the block, the sequence and fixation time was randomized from trial-to-trial. Prior to each experimental block, subjects completed a block of calibration trials consisting of

reactive movements from fixation to each of the eight targets (presented randomly) used in the experimental block (10 saccades to each target, 80 trials total).

Analysis of the saccadic amplitudes and directions was done off-line. Saccade onset was found using velocity and acceleration criteria (exceeding both $80^\circ/\text{s}$ and $5000^\circ/\text{s}^2$). We analyzed saccade sequences where subjects made only two saccades to the two targets and the first saccade occurred after the targets had disappeared, that is, the first saccade latency was more than the total duration of the two targets (170 ms). There were no maximum latency criteria for first saccades but they occurred within 500 ms of when the fixation point was turned off in all conditions for all subjects. The mean latency of the first and second saccade of the sequence for each subject for the three conditions are shown in Table 1. For each condition, we measured the direction (ϕ) and amplitude (α) of the second saccade of the sequence as depicted in Figure 2.

RESULTS

Amplitude Compensation For Horizontal and Vertical Saccades

Our first aim was to demonstrate in humans that the angle of the second saccade in the double step task compensated for variations in amplitude of the first saccade as previously reported for the monkey (Sommer & Wurtz, 2004b). We used horizontal first saccades (condition 1, Figure 2, left), and for analysis we represented the saccades as straight line vectors between each saccade's initial and final position. Figure 3A shows this vector representation for a sample subject and a sample target sequence for which only the longest and shortest first horizontal saccades made to the 10° target-strip are shown. The origin of the second saccade vector is placed at the horizontal endpoint of the first saccade. For this shortest first saccade (gray), the second saccade angles forward, and for the longest first saccade (black), the second saccade angles back. Figure 3B displays all the second saccade vectors in this sample ordered according to the length of the first saccade. For ease of display, the saccade vectors are arbitrarily separated vertically. The vectors clearly show a change in direction dependent on the endpoint of the first saccade.

Our second aim was to test for compensation when the initial saccade was a vertical one (not tested in the monkey, Sommer & Wurtz, 2004b) as shown in condition 2 (Figure 2, center). We found that the angle of the second horizontal saccade also compensated for long and short initial vertical saccades (Figure 3C).

Figure 4A displays the eye movement traces for the same subject for the horizontal-vertical saccade sequence (red traces) and the vertical-horizontal saccade sequence (blue traces). Note that the endpoints of the second saccade for most conditions converge, demonstrating that there is more variability in the initial position of the second saccade than in the final position. (For all subjects there was more variability in the initial position of the second saccade than in the final position, but this difference was only significant in 11 out of 40 cases ($P < 0.05$, F -test) and there tended to be less of a difference for vertical first saccades.) This again reveals a trial-by-trial adjustment in the second saccade direction based on the length the first saccade.

To quantify this adjustment, for each trial we determined the angle of the second saccade vector whose origin was at the end of the first saccade, and compared that to the ideal angle required for the subject to reach the target. Figure 4B and C show the actual angle of the second saccade plotted against the ideal angle for the horizontal-vertical and vertical-horizontal saccade sequences for the four target sequences. The slope and R^2 values of the regression analysis between the two angles are indicated in each panel and all regressions were significant ($P < 0.05$). As revealed by the regression analysis, the subject compensated more for initial

horizontal saccade variations than for vertical saccade variations, and performance for some target sequences were better than for others.

For the five subjects, we pooled the data for the four target sequences in the horizontal-vertical and vertical-horizontal trials (Figure 5A and 5B). The R^2 values of the regression analysis were significant in all cases ($P < 0.05$). As was the case for the sample subject presented in Figure 4, the five subjects tended to make the second saccade adjustment better for horizontal first saccades than for vertical first saccades. Across the five subjects we then quantified the saccade direction compensation by averaging the four regression slopes determined independently for each target sequence. The percent angle compensation was the scaling of this average. (For example, if the average regression slope was 0.95 then the percent angle compensation was 95%.) The bar graphs in Figure 5C summarize this percentage for each subject for the horizontal-vertical (red) and vertical-horizontal saccade sequence (blue). Shown at the bottom of Figure 5C is the average percent compensation across the five subjects. The percent angle compensation was significantly greater for horizontal than for vertical movements (100% and 74% respectively, two-tailed t -test, $P < 0.001$). In addition, the average percent compensation for the horizontal-vertical saccade sequence condition was similar to that reported previously for monkeys (97% Sommer & Wurtz, 2004b).

Angle and Amplitude Compensation Following Oblique Saccades

Our third aim was to determine whether there was saccade-by-saccade compensation in the amplitude of the second saccade as well as in its angle. For the horizontal and vertical saccades studied so far, we examined the amplitudes of the second saccades. Unlike the results for the second-saccade angle, we found no consistent significant correlation between actual and ideal saccade amplitudes ($P > 0.05$ in 21 out of 40 cases). This is not surprising because for both sequence conditions the endpoint variability of the first saccade results in a range of ideal saccade angle adjustments that is considerably larger than the range of corresponding saccade amplitude adjustments. Consider the second saccade vectors (gray arrows) depicted in Figure 1B. The required angle of the saccade vector to reach the target after overshooting or undershooting the first target is substantially different, but the ideal amplitude of the same saccade vectors is similar.

In order to circumvent this problem, we examined oblique saccades (condition 3, Figure 2C) which would be more likely to reveal adjustments in amplitude as well as in angle of the second saccade (Figure 1C). Figure 6A shows the eye movement traces for oblique saccades for the same subject as in Figures 3 and 4. Figure 6B and C show the actual angle and amplitude of the second saccade plotted against the ideal angle and amplitude. As in the results for the horizontal-vertical and vertical-horizontal saccade sequences, performance for some target sequences were better than for others, but all conditions revealed amplitude adjustments in the second saccade and all regressions were significant ($P < 0.05$). Thus, when the adjustment required in saccade amplitude was substantial, the subject adjusted the amplitude as well as the angle of the second saccade.

To quantify the adjustment in saccade direction and amplitude for each subject we again plotted actual saccade amplitudes and directions against ideal performance (Figure 7A and B). Slope and R^2 values are indicated in each panel, and all regressions were significant ($P < 0.05$). As for the sample subject presented in Figure 6, subjects adjusted similarly for both saccade direction and amplitude.

The bar graphs in Figure 7C and D summarize the average of the four regression slopes for the oblique saccade sequence for angle and amplitude determined independently for each target sequence. The graph shows that on average the subjects adjusted the second saccade near 90% for both direction and amplitude.

DISCUSSION

If a CD is generated with each saccade, we would expect to see evidence of it in subsequent saccades that depended upon that CD. The double-step saccade task tests this dependence: successful completion of the second saccade requires subjects to utilize the CD of the preceding first saccade. In the present experiments on humans, we determined whether variations in the amplitude of the first saccade (which must be represented in the CD) are used to adjust the second saccade. We made three observations that indicate that the CD is used by the second saccade. First, we found that the direction of vertical saccades following the first horizontal saccades, compensate for variations in amplitude of the first saccades as had been found in the monkey. Second, the change in direction of the second saccade is present following both horizontal and vertical first saccades, although the compensation was significantly greater for horizontal saccades. Third, by examining oblique saccades, we showed that both the amplitude and direction of the second saccade were modified to compensate for the variations in the amplitude of the first saccade.

These observations provide strong evidence that the variations in the CD of previous saccades are used to adjust the direction and amplitude of the current saccade. This saccade-by-saccade compensation is consistent with previous observations in humans and monkey, and its characteristics are consistent with the known neuronal basis of the CD, which we discuss below.

Compensation by Humans for Variations in Individual saccades

We find compensation on a saccade-by-saccade basis in humans just as had been found previously in monkeys. For horizontal first saccades, where a direct comparison with monkeys could be made, the magnitude of the adjustment is nearly complete: $100 \pm 11\%$ in humans; 97% in monkeys.

While our subsequent experiments go beyond this to show that compensation occurs in both the direction and the amplitude of the saccade, the basic observation of saccade-by-saccade compensation is consistent with several previous observations in humans. A similar compensation was recently demonstrated in humans by Munuera et al.(2009) in a modified double-step task in which the first step was to a visible target and the second step was to a remembered target. Following a horizontal saccade to the first target, variations in the eye position produced by that first saccade were partially compensated by the changes in the second saccade to the remembered target. The compensation became larger with larger saccades (6° to 18°) and also when the target was moved to evoke a corrective saccade. No attempt was made to dissociate the direction and amplitude of the second saccade in these experiments (Munuera et al., 2009), but the authors did show the same basic finding that the guidance of sequential saccades is dependent upon an extraretinal signal. However, they found a maximum compensation of only 29% which is substantially below our finding and those of other studies cited below.

The contribution of an extraretinal signal to a series of saccades was suggested by several previous experiments that analyzed compensation over a series of saccades. Bock et al. (1995) found that over a sequence of four saccades made to remembered targets in the dark about 60% of the accumulated errors were corrected. Ditterich, Eggert, and Straube (1998) tested the same type of error correction over a series of saccades to up to five remembered targets. They found that they could divide sequences of saccades into two modes: one with fixed amplitudes resulting from preprogramming with little compensation; one with nearly 100% percent compensation that were presumably not preprogrammed. The authors suggested that the lower measured compensation in some studies resulted from mixing these two modes.

In summary, all of the studies show compensation that can be the result of a CD, and the compensation can be as high as 100% even over a series of saccades. Our finding of compensation near 100% in humans when measured over individual saccades and using the sensitivity of the eye coil recording technique provides substantial further evidence of the use of a CD to guide sequential saccades when vision is not available.

Relation of Compensation in Humans to Neuronal Mechanisms in Monkeys

In the present experiments we have established two additional characteristics of the compensation for saccadic variation. First, the compensation occurs for vertical as well as horizontal saccades, and while this is not surprising, it had not previously been established in either humans or monkeys. Second, the compensation is expressed in both the direction and the amplitude of the saccade. Both attributes of the compensation may be better understood by comparing these results to what is known about the underlying neuronal mechanisms of the CD as studied in the monkey.

In comparing the compensation following horizontal and vertical first saccades, we found that the CD of horizontal saccades is more accurate than that for vertical (Figures 4 and 5). Though there were differences in the amount of compensation for upward and downward saccades within a given subject, these differences were not consistent across subjects and compensation for vertical first saccades tended to be worse than horizontal first saccades made to reach the same endpoint. While there is no obvious correlate of this in the neuronal circuitry related to either saccade generation or the CD, one possible explanation for this finding is the representation of these vertical saccades on the movement map in the superior colliculus, which is the source of the corollary discharge pathway to frontal cortex in the monkey (Sommer & Wurtz, 2004a). A vertical first saccade should activate movement fields along the vertical meridian that are represented in both superior colliculi in contrast to a horizontal first saccade that is represented in only one (Goldberg & Wurtz, 1972, Robinson, 1963). The representation of the vertical saccades in both colliculi might be slightly more ambiguous than for the horizontal saccades to targets represented entirely in one colliculus. Consistent with this idea of the role of the vertical meridian is lack of any systematic difference in the horizontal and vertical saccadic component of oblique saccades. These saccades incorporated a vertical component to the movement, but not the vertical meridian, and subjects were able to make a CD-based correction in saccade direction similar to that demonstrated for horizontal movements. This further suggests that the loss in CD accuracy occurs specifically for saccades along the vertical meridian and not just for saccades with a vertical component.

Our second observation that may be related to the underlying neuronal mechanism of the CD is that both the direction and amplitude of the second saccade is adjusted based on the CD of the first saccade (Figures 6 and 7). Most previous studies of the double-step paradigm have focused solely on saccade angle (Bock et al., 1995, Duhamel et al., 1992, Munuera et al., 2009) or amplitude (Ditterich et al., 1998, Heide, Blankenburg, Zimmermann & Kompf, 1995). Few studies have examined both aspects of the second movement though the CD should provide information on both components of the saccade. Any trial-by-trial adjustment in the second saccade amplitude for purely horizontal or vertical saccades in previous reports was likely obscured by the noise of the second saccade. Take for example the schematic outlined in Figure 1B. The vertical variability of the horizontal first saccade endpoints (height of red ellipse) is significantly smaller than the vertical variability of the vertical second saccade (height of blue ellipse) (van Beers, 2007). Here, by examining oblique saccades, we have shown a trial-by-trial adjustment in the second saccade amplitude, as well as the saccade direction. The amount of error adjustment was consistent with that reported in previous studies of human subjects (Bock et al., 1995, Ditterich et al., 1998). Previous reports examining different patient groups have suggested that various brain regions may be involved in utilizing the CD in

adjusting the direction of movements (Bellebaum, Daum, Koch, Schwarz & Hoffmann, 2005, Bellebaum, Hoffmann, Koch, Schwarz & Daum, 2006, Duhamel et al., 1992, Heide et al., 1995). Based on the results presented here, it may be fruitful to determine if these deficits are also present for movement amplitude by using oblique saccades.

The finding of both direction and amplitude adjustments also resolves an anomaly between the observations of direction compensation in the initial psychophysical observations and the characteristics of the neurons conveying the CD in monkeys. The superior colliculus neurons and the neurons in medial dorsal thalamus conveying the CD to the frontal cortex are related to saccades of a given amplitude and direction (Goldberg & Wurtz, 1972, Robinson, 1963, Sommer & Wurtz, 2004b). They essentially convey the vector of the impending saccade. The finding that compensation seemed to be just a change in direction of the second saccade did not fit the neuronal characteristics of the CD. The recognition that both the direction and amplitude of the second saccade contribute to the compensatory changes following oblique saccades resolves the discrepancy between the CD evidence from behavior and that from neuronal activity. Both now are consistent with the inferred CD representing a vector for direction and amplitude of the executed saccade.

Acknowledgments

Supported by the National Eye Institute Intramural Research Program. We are grateful for the continuing advice of our colleague Christian Quaia during these experiments, and for discussions with Neeraj Gandhi, Rebecca Berman and Richard Krauzlis.

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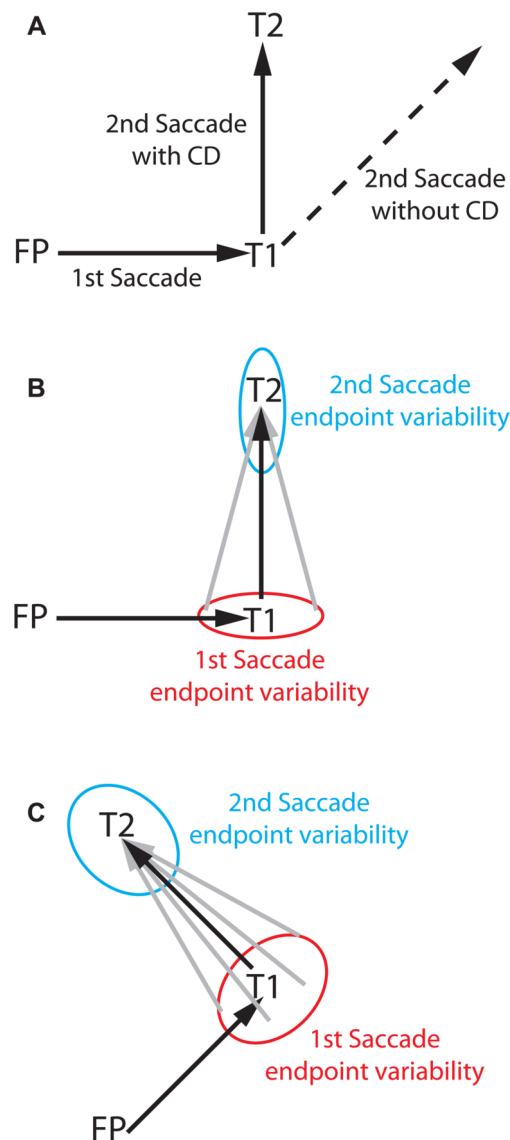


Figure 1. Schematic of behavior during the double-step task

(A) Typically, in the double-step task, the subject is required to make a horizontal saccade from the fixation point (FP) to the horizontal target (T1) and then from there to make a vertical saccade to the vertical target (T2). Because both targets are extinguished before saccade onset, the vertical second saccade can only be accurately made if the position of the eye after the first saccade is known (with CD). Without the CD the subject would make a diagonal saccade corresponding to the location of the second target with respect to the original fixation position. (B) When subjects perform the task there is variation in the amplitude of the horizontal first and vertical second saccade (depicted by the red and blue ellipses). On a trial-by-trial basis the CD of the first saccade is used to compensate for the initial error (overshooting or undershooting the first target) and correctly direct the second saccade to the second target (gray arrows). (C) When subjects make oblique saccades in the double step task there is variability in the both the amplitude and direction of the first movement (depicted by the red ellipse). In this case the second saccade reveals a CD-based compensation in both amplitude and angle (gray arrows).

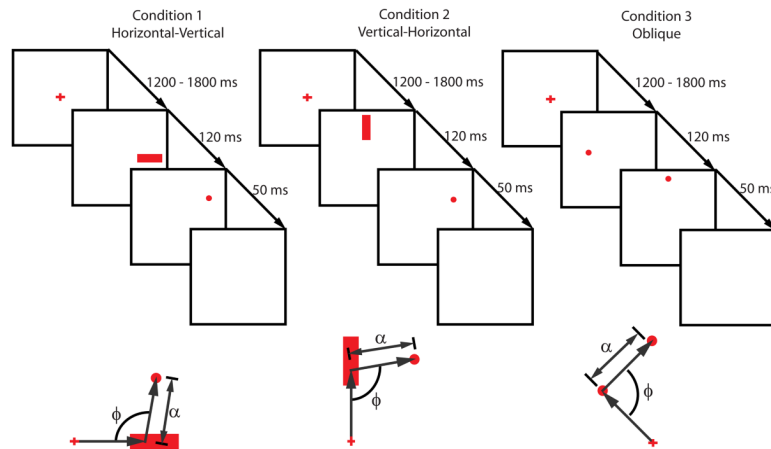


Figure 2. Experimental paradigm and target sequences

Subjects made two saccadic eye movements for three different target conditions of the double-step paradigm. Each trial began with fixation at the center target, followed by the offset of the fixation point and sequential appearance of two peripheral targets (either a diffuse strip or spot). The subject's task was to make a saccade to the location of the first and then the second target. The conditions differed in the shape and orientation of the targets. In condition 1 the first target was a horizontal-oriented strip (4° by 2°) centered either to the right or left of fixation ($\pm 10^\circ$, 0) followed by a second target (a spot 0.3° in size) flashed 10° vertically above or below the strip. In condition 2 the first target was a vertical-oriented strip centered above or below fixation (0 , $\pm 10^\circ$) followed by the spot target flashed 10° horizontally to the left or right of the strip. In condition 3 the first target was a spot located diagonally from fixation (either at $-7.1^\circ, 7.1^\circ$ or $7.1^\circ, -7.1^\circ$) followed by a spot located 10° orthogonal from the first. For example, in the example presented, the second spot for condition 3 appeared at $(0, 14.1^\circ)$. Each condition had four possible target sequences, of which only one is depicted. For each condition, we measured the direction (ϕ) and amplitude (α) of the second saccade of the sequence.

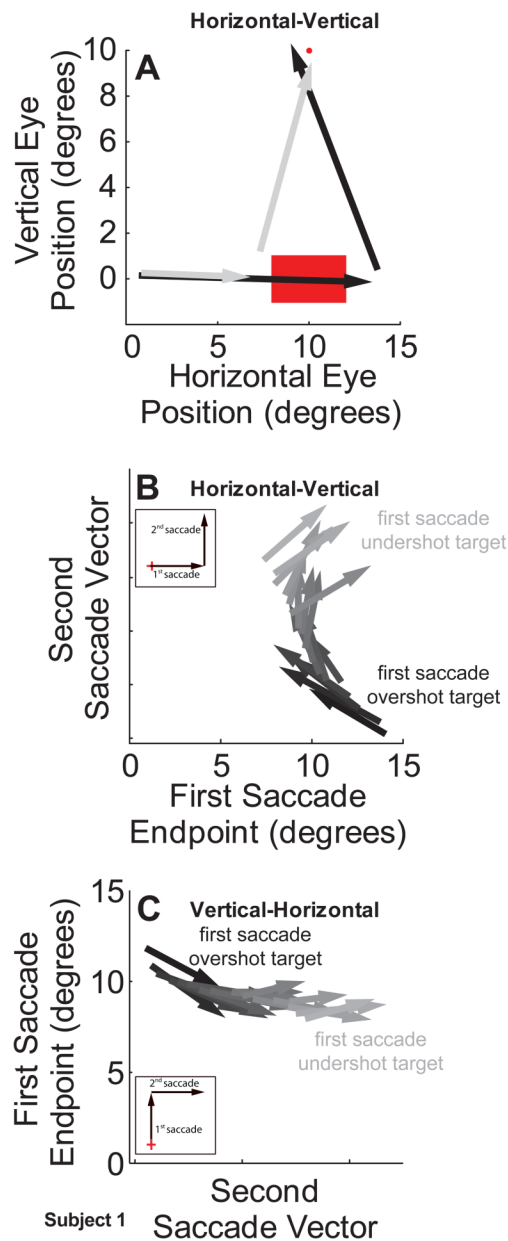


Figure 3. Examples of direction changes of the second saccade with variations in amplitude of the first saccade

To depict how the direction of the second saccade was influenced by the corollary discharge of the first saccade, the saccades are represented as vectors: a straight line connecting the initial and final position of the saccade, ending with an arrowhead that represents the movement direction. (A) Example of the second saccade direction for the longest and shortest saccades made by a sample subject. When the first saccade fell short (gray arrows) or extended beyond (black arrows) the horizontal center of the first target (the red horizontally-oriented strip centered at 10°), the subject angled the second saccade in the direction of the second target (small red spot at 10°, 10°). (B) Vectors of the second saccades in order of first saccade endpoint for the sample subject for horizontal first saccades (C) and vertical first saccades. In both examples there is clearly a change in the direction of the saccade vectors dependent on the endpoint of the first saccade. The insert in (B) and (C) describe the saccade sequence of the

presented data. Note that the saccade vectors are arbitrarily separated vertically in **(B)** and horizontally in **(C)** to show the difference in the second saccade direction.

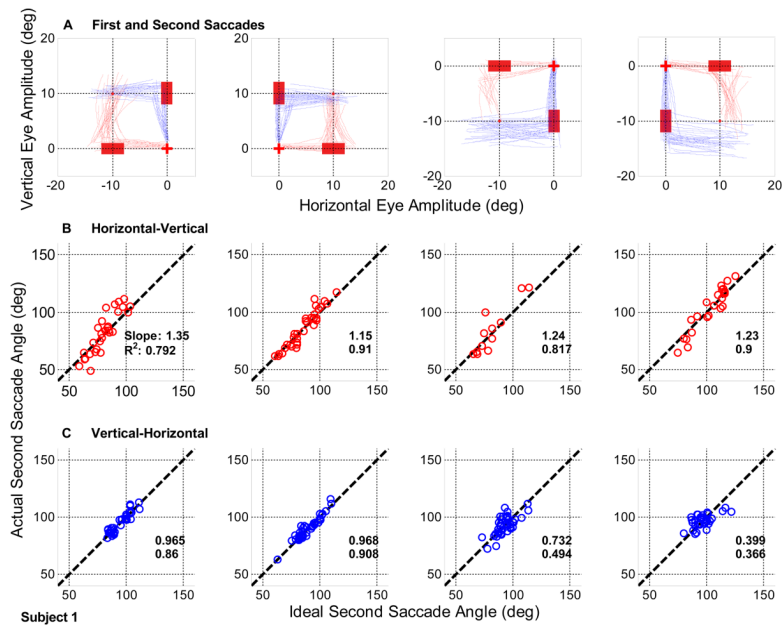


Figure 4. Changes in direction of second saccades for one subject

(A) The eye movement traces for horizontal first saccades (condition 1, red traces) and vertical first saccades (condition 2, blue traces) for the four target sequences. The fixation point, and start of the first saccade, is represented by the red cross. The first and second target, the red horizontal and vertical-oriented strips and small spots, are also displayed. In the two left columns the horizontal saccades are made to the left or to the right and the vertical saccade is up. In the two right columns the horizontal saccades are made to the left or to the right and the vertical saccade is down. (B and C) The actual second saccade angle plotted against the ideal second saccade angle (angle required to reach the target) for the four target sequences for horizontal - vertical and vertical - horizontal saccades. The slope and R^2 values of the regression analysis between the two angles are indicated in each panel.

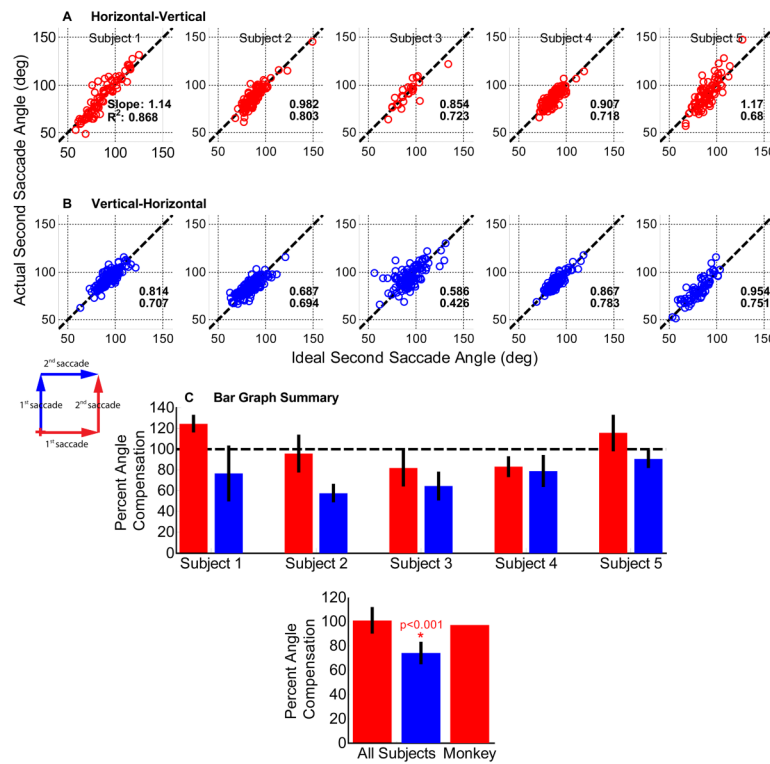


Figure 5. Changes in direction of second saccades for all subjects

(A and B) For each subject, the actual angle of the second saccade is plotted against the ideal angle for horizontal - vertical (red) and vertical - horizontal saccades (blue). Each graph combines the data from all four target sequences. (C) The bar graphs summarize the percent angle compensation (regression slope between actual and ideal angle) for each subject. The height of each bar represents the average of the four regression slopes determined individually for each target sequence. Vertical lines represent standard deviation. (D) The mean percent angle compensation for horizontal - vertical and vertical - horizontal saccades across subjects was approximately 100% and 75% respectively. This difference in percent compensation was significant (two-tailed *t*-test, $P < 0.001$). The average percent angle compensation for horizontal - vertical saccades is similar to that reported previously for monkeys (97%, Sommer & Wurtz, 2004b, 2008).

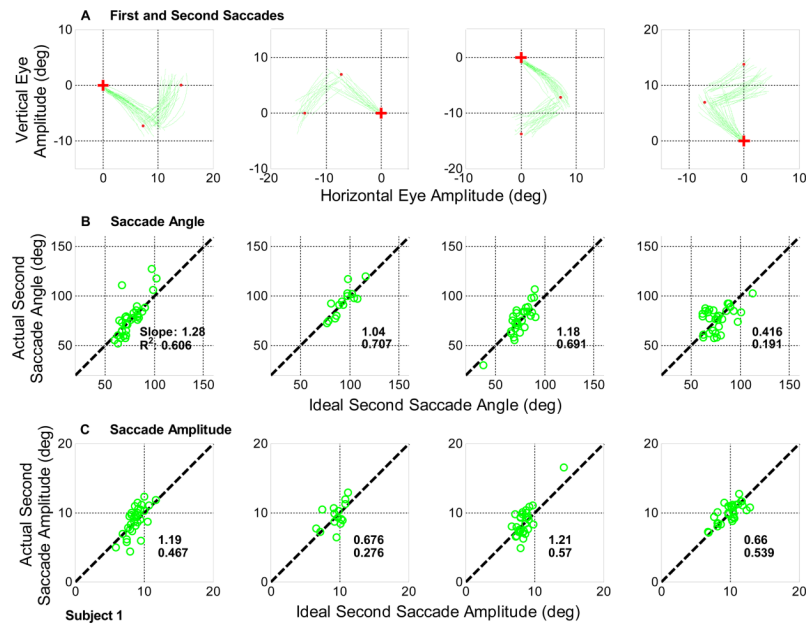


Figure 6. Changes in direction and amplitude in oblique saccades for one subject

(A) The eye movement traces for a sample subject for oblique saccades for the four target sequences. The fixation point, and start of the first saccade, is represented by the red cross. The first and second target, the small red spots, are also displayed. The actual angle (B) and amplitude (C) of the second saccade plotted against the ideal angle and amplitude (angle and amplitude required to reach the target) for the four target sequences.

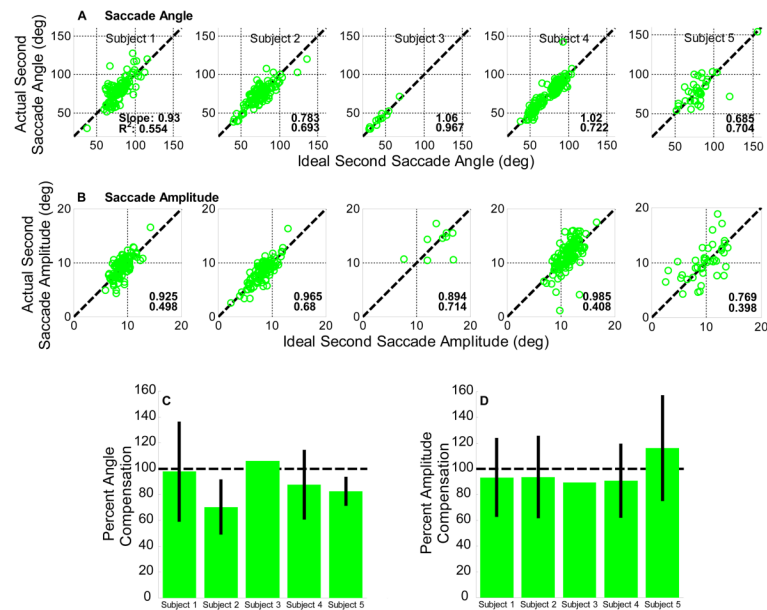


Figure 7. Changes in direction and amplitude in oblique saccades for all subjects

For each subject, the actual angle (**A**) and amplitude (**B**) of the second saccade is plotted against the ideal angle and amplitude for the oblique saccades for the four target sequences. The data displayed is the combined data from all four target sequences. The bar graphs summarize the percent compensation (regression slope between actual and ideal values) for angle (**C**) and amplitude (**D**) for each subject. The height of each bar represents the average of the four regression slopes determined individually for each target sequence. Vertical lines represent standard deviation. (Note that subject 3 does not have error bars since there were too few trials for three of the four target sequences.)

The mean latency of the first and second saccade of the sequence for each subject for the three conditions. The latency of the first saccade was determined from the time when the fixation point was turned off. The latency of the second saccade was determined from the time of the first saccade.

Table 1

| | Condition 1 Latencies (ms) | | Condition 2 Latencies (ms) | | Condition 3 Latencies (ms) | |
|------------------|----------------------------|----------------|----------------------------|----------------|----------------------------|----------------|
| | First Saccade | Second Saccade | First Saccade | Second Saccade | First Saccade | Second Saccade |
| Subject 1 | 309.4 ± 92.1 | 450.6 ± 98.9 | 233.3 ± 42.0 | 407.9 ± 51.1 | 405.9 ± 39.0 | 387.0 ± 56.6 |
| Subject 2 | 193.9 ± 15.9 | 182.4 ± 110.4 | 201.5 ± 13.5 | 121.8 ± 39.9 | 438.6 ± 75.0 | 470.9 ± 78.3 |
| Subject 3 | 238.2 ± 63.5 | 369.3 ± 126.3 | 228.8 ± 43.5 | 362.1 ± 166.0 | 385.0 ± 118.9 | 692.8 ± 189.3 |
| Subject 4 | 284.2 ± 70.4 | 717.4 ± 153.3 | 309.6 ± 61.1 | 709.4 ± 125.6 | 384.2 ± 56.6 | 745.5 ± 238.6 |
| Subject 5 | 264.0 ± 68.9 | 421.0 ± 150.9 | 314.1 ± 92.6 | 570.9 ± 164.5 | 247.6 ± 97.7 | 452.5 ± 180.2 |
| Average | 258.6 ± 77.7 | 450.0 ± 240.8 | 252.6 ± 68.2 | 424.8 ± 241.0 | 388.8 ± 90.2 | 572.7 ± 226.1 |