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Havermann K, Zimmermann E, Lappe M. Eye position effects in saccadic adaptation. *J Neurophysiol* 106: 2536–2545, 2011. First published July 27, 2011; doi:10.1152/jn.00023.2011.—Saccades are used by the visual system to explore visual space with the high accuracy of the fovea. The visual error after the saccade is used to adapt the control of subsequent eye movements of the same amplitude and direction in order to keep saccades accurate. Saccadic adaptation is thus specific to saccade amplitude and direction. In the present study we show that saccadic adaptation is also specific to the initial position of the eye in the orbit. This is useful, because saccades are normally accompanied by head movements and the control of combined head and eye movements depends on eye position. Many parts of the saccadic system contain eye position information. Using the intrasaccadic target step paradigm, we adaptively reduced the amplitude of reactive saccades to a suddenly appearing target at a selective position of the eyes in the orbitae and tested the resulting amplitude changes for the same saccade vector at other starting positions. For central adaptation positions the saccade amplitude reduction transferred completely to eccentric starting positions. However, for adaptation at eccentric starting positions, there was a reduced transfer to saccades from central starting positions or from eccentric starting positions in the opposite hemifield. Thus eye position information modifies the transfer of saccadic amplitude changes in the adaptation of reactive saccades. A gain field mechanism may explain the eye position dependence found.

eye position signal; motor learning; oculomotor control

WITH SACCADIC EYE MOVEMENTS, the oculomotor system directs the foveae to points of interest in a scene. Saccadic adaptation is a process that controls the accuracy of a saccade by adjusting its gain when the movement did not reach its target. The mechanisms underlying saccadic adaptation are studied in the paradigm of intrasaccadic target displacement (McLaughlin 1967), in which the saccade target is displaced while the saccade is in flight, thereby creating an artificial postsaccadic error. Saccades are stereotyped and ballistic; therefore saccadic success is monitored after the saccade and the saccadic motor plan for subsequent saccades is modified after movement execution, if necessary.

Studies using the intrasaccadic target displacement paradigm have shown that saccadic adaptation is specific to the direction and amplitude of the saccade, consistent with the view that the oculomotor system codes saccades primarily by means of their motor vector (Hopp and Fuchs 2004; Pelisson et al. 2010). However, there are at least two reasons why adaptation may also be specific to initial eye position, i.e., include information beyond the motor vector.

First, same-amplitude saccades from different starting positions in the orbit need different eye muscle control. Thus at least the late stages of oculomotor control need to take eye position into account, and so should adaptive processes that compensate for muscle weakness or fatigue (Groh 2010; Ling et al. 2007; Sylvestre and Cullen 1999). Second, saccades larger than a couple of degrees are normally accompanied by head movements (Guitton 1992). In this case, the control signal of the oculomotor system is a gaze shift command, i.e., a command for a combination of eye and head movements to result in a shift of gaze to the target (Freedman and Sparks 1997; Munoz et al. 1991), and the intrasaccadic target displacement paradigm shows adaptation of the gaze shift control (Cecala and Freedman 2008a, 2008b; Phillips et al. 1997). The gaze shift command must be decomposed into head and eye components to drive the respective effectors, since the relative contributions of eye and head components to a gaze shift depend on initial eye position (Freedman 2008). Like the low-level control of eye kinematics, the decomposition into eye and head components is performed in late stages of oculomotor control.

There are also theoretical arguments for an inclusion of information beyond the motor vector in saccadic adaptation. For an optimal adaptation of oculomotor control the system should perform an assessment of the possible origins of any postsaccadic visual error, i.e., an attribution of this error to one or more of several possible causes (Kording et al. 2007; Wei and Kording 2009). For such a process, information about body movements is crucial to differentiate external from internal error sources during natural behavior. Eye position, in this sense, allows us to distinguish visual errors due to failures of saccade control from visual target displacements due to intervening head movements. It connects eye movements with head postures in a retinotopic to craniotopic coordinate transformation. Many parts of the saccadic system contain eye position signals, which allow eye position-dependent oculomotor control.

In a schematic view of the oculomotor system, two large circuits interact in the control of saccades. One loop includes the brain stem burst generator (BBG), the cerebellum, the nucleus reticularis tegmenti pontis (NRTP), and the superior colliculus (SC). This cerebellar-collicular-brainstem loop controls saccade kinematics. Furthermore, a cortical loop including the frontal eye field (FEF) and the lateral intraparietal area (LIP) influences the BBG directly and via the SC. This cortical loop is believed to take part in higher aspects of saccade control, such as target selection, attention, and memory.

Both loops show dependencies on eye position in the generation of saccades. After lesions or inactivation of the cerebellum, saccades deviate systematically from the correct am-

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plitude depending on the initial eye position (Ritchie 1976; Robinson et al. 1993). Furthermore, eye position influences the activity of some single neurons in the fastigial nucleus (Fuchs et al. 1993) and the NRTP (Crandall and Keller 1985) during saccade generation.

In the SC neuronal firing rates are modulated mainly by the saccade vector but also by the orbital eye position. This modulation has the form of an eye position gain field (Campos et al. 2006; van Opstal et al. 1995). Eye position gain fields were first described by Andersen and Mountcastle (1983) and Zipser and Andersen (1988) and can be found among other areas in area LIP (Andersen et al. 1990) and the FEF (Cassanello and Ferrera 2007) in the cortical saccade loop. The origin of the eye position modulation may lie in a representation of eye muscle proprioception in the somatosensory cortex (Wang et al. 2007).

In summary, therefore, the fastigial nucleus and vermis of the cerebellum, the NRTP, the SC, the LIP, and the FEF possess the potential for eye position-dependent effects within the saccadic circuitry.

Therefore we can expect that the eye position information encoded in the saccadic system via gain field modulations is also present in the adaptive control of oculomotor performance. This would predict an eye position-specific saccadic adaptation.

The specificity of saccadic adaptation to eye position has previously been tested with two different experimental paradigms. In the first paradigm, saccades at one particular starting position were adapted and the transfer of adaptation to similar saccades starting from other spatial locations was tested (Albano 1996; Deubel et al. 1995; Frens and Opstal 1994; Semmlow et al. 1989). These tests usually gave strong transfer from the adapted eye position to the tested eye positions, concluding that saccadic adaptation is retinocentric. The second paradigm tested whether saccades that started from two different spatial positions could be adapted differently (Alahyane and Pelisson 2004; Semmlow et al. 1989; Shelhamer and Clendaniel 2002; Tian and Zee 2010; Watanabe et al. 2000). These studies collectively found that it was possible to adapt saccades at one eye position in one way and, simultaneously, adapt saccades at another eye position in another way. They concluded that saccadic adaptation can depend on eye position as a contextual cue to resolve the situation of conflicting error information at the two positions. In the present study we revisit the first paradigm to determine whether the retinocentric encoding of saccadic adaptation is modulated by eye position as an inherent factor even without conflicting errors.

MATERIALS AND METHODS

Stimuli and recording setup. The subject sat at a distance of 57 cm from a 22-in. monitor (Eizo FlexScan F930). This resulted in a visual field of 40° × 30°. The room was completely dark. A transparent foil reduced the luminance of the monitor by 2 log units and minimized the visibility of the monitor borders. Stimuli were presented with a refresh rate of 120 Hz and a resolution of 600 × 800 pixels. The stimuli were white squares, 0.75° × 0.75°, with a luminance of 0.5 cd/m^2. Eye movements were recorded with the EyeLink 1000 system (SR Research) at a 1,000-Hz sample rate. For all subjects the left eye was recorded. Viewing was binocular. The subject's head was fixed with a bite bar. Before starting the experiment participants gave informed consent in accordance with the Declaration of Helsinki and the guidelines of the local ethics committee (Department of Psychology, University of Muenster, Germany), which approved this study.

Experimental procedure. The adaptation procedure was carried out according to a modified McLaughlin (1967) paradigm. The subject performed a saccade to a suddenly appearing target. Simultaneously with the appearance of the target, the fixation point was turned off. During the saccade, a displacement of the target was introduced that resulted in a postsaccadic visual error. Over the course of many trials the saccadic amplitude then adapted in the direction of the displacement.

Five equally distributed fixation positions in a horizontal plane with a distance of 5° between neighboring fixation positions were used to test for an eye position effect (Fig. 1). In a single session, saccades originating from one of the five fixation positions were adapted via the target backstep procedure. Thereafter, the amount of adaptation at all five positions was tested.

The same experiment was afterwards repeated for a vertical alignment of initial eye positions. The experimental protocol was identical to the first experiment, with the exception that the test positions were

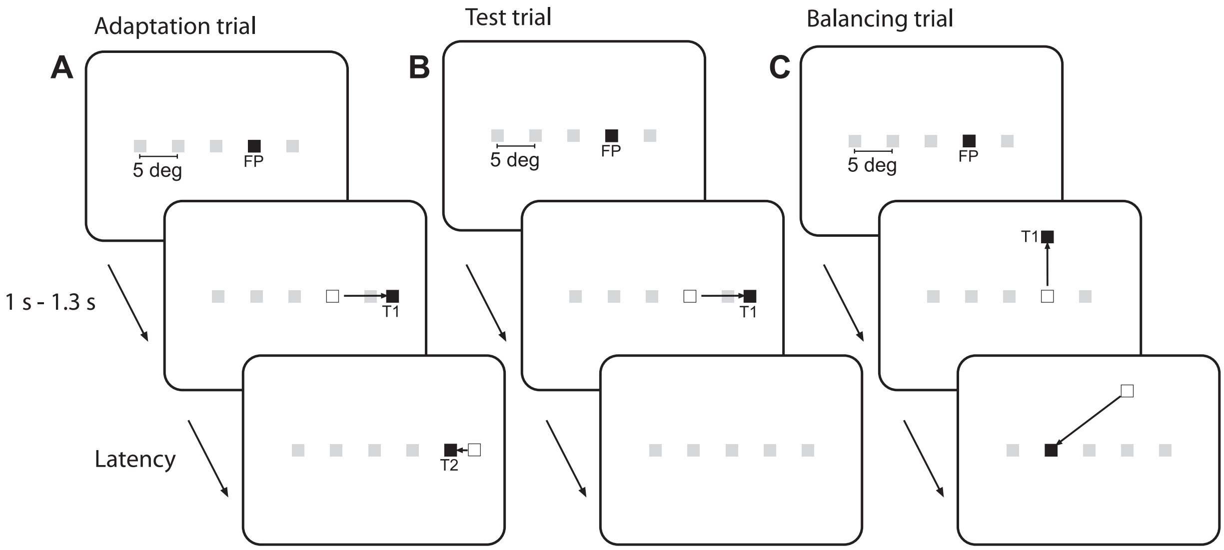

Fig. 1. Schematic view of the different types of trials. Gray squares show all 5 possible initial eye positions. Filled square shows the target positions; open square shows the former target position. *A*: adaptation trial; after a variable fixation duration the appearance of the target evokes a saccade. The onset of the saccade then triggers the intrasaccadic backstep. *B*: in test trials, the target is extinguished during the saccade. *C*: balancing trial.

arranged vertically. Five test positions were placed 5° apart along the vertical meridian. Position 0° was aligned with the eye level of the subject. Positions −10° and −5° were located below and positions 5° and 10° above eye level.

Every adaptation session consisted of three phases, a preadaptation phase, an adaptation phase, and a postadaptation phase. The preadaptation phase served to obtain baseline data for each initial eye position. All positions were tested with five test trials in random order. Preadaptation data from the five sessions were combined such that the baseline from every test position was calculated from 25 repetitions. The preadaptation phase was followed by the adaptation phase, which consisted of 88 adaptation trials and 44 pseudorandomly interleaved balancing trials described below. In the postadaptation phase, each initial fixation position was tested with 20 test trials. After each test trial, two adaptation trials at the adaptation position were interleaved to retain the subject in the adapted state. Therefore the postadaptation phase consisted of 300 trials. In total, one session therefore consisted of 457 trials. To avoid blinking during adaptation and test saccades, every 10 trials the fixation point turned red and stayed red for an additional second to allow blinking.

Figure 1*A* shows the events during a single adaptation trial. The trial started with a fixation at one of the five initial eye positions. The saccade target appeared 7° to the right of the fixation point after a fixation duration of 1,000 ms plus a random delay of up to 300 ms. The subject was instructed to make the saccade as soon as the target appeared. When the eye position crossed a threshold 2° right from the fixation point the saccade target stepped 2° inward, i.e., to the left. After a further 800 ms the target disappeared and the fixation point of the next trial appeared.

Next to these adaptation trials each adaptation session contained test trials for the other eye positions. In these test trials (Fig. 1*B*), one of the five possible fixation points appeared. As in the adaptation trials, the saccade target appeared 7° to the right of the fixation point after a fixation duration of 1,000 ms plus a random delay of up to 300 ms. When the subject initiated the saccade and the eye position crossed the threshold 2° right from the fixation point the saccade target disappeared. Eight hundred milliseconds later the fixation point of the next trial appeared. The target was extinguished to prevent visual feedback that could interfere with the adaptation. If the target remained illuminated and the saccade was too short (because it was partially adapted), the resulting visual error would lead to gain-increasing adaptation or deadaptation. All saccadic amplitudes in the preadaptation phase and in the postadaptation phase were calculated on the basis of test trials.

Furthermore, balancing trials (Fig. 1*C*) were intermixed to balance the eye positions throughout the adaptation phase of the session. These trials were added to avoid the situation that eye position was off to one side almost all through a session. In a balancing trial a 7° upward saccade was followed by a saccade to the symmetrical fixation position along the horizontal or vertical axis, respectively. For example, if the leftmost eye position served as adaptation position, the balancing position was at the rightmost eye position.

Every subject performed 10 sessions, 5 for horizontal and 5 for vertical arrangements of initial eye positions. Successive sessions with the same subject were separated by 5 days on average and by at least 24 h. We checked for possible retention effects between successive sessions (Alahyane and Pelisson 2005) by comparing amplitudes in the preadaptation conditions in subsequent sessions. We found no retention effects. A two-factor repeated-measures ANOVA on the preadaptation amplitudes showed no significant difference between sessions [horizontal: $F(4,20) = 0.36$, $P = 0.83$; vertical: $F(4,16) = 2.17$, $P = 0.12$] or between test positions [horizontal: $F(4,20) = 0.66$, $P = 0.63$; vertical: $F(4,16) = 2.26$, $P = 0.11$].

Subjects. Six subjects took part in the experiment with horizontal eye position dependence (1 author, 1 man, 5 women, all right handed; mean age 25.5 yr). Five of these subjects participated in the experiment with vertically aligned test position (1 author, 1 man, 4 women, all right handed; mean age 25.2 yr).

Data analysis. For data analysis the saccadic amplitude for the preadaptation trials and for the postadaptation trials was calculated for every test position in every adaptation session of every subject. Eye movements detected by the EyeLink software were used for analysis. The criteria involved a 22° velocity threshold and a 4,000°/s^2 acceleration criterion. Saccades that started before the appearance of a target, or that were shorter than 1°, were excluded from the analysis. This occurred in 9% of all trials.

The mean preadaptation amplitude was calculated for each subject as the average of all adaptation sessions for each initial eye position. Therefore a unique averaged preadaptation amplitude was determined for each subject at each of the five test positions. The amplitude change was calculated as the difference of preadaptation amplitudes and postadaptation amplitudes at each of the five initial fixation positions such that positive values correspond to an amplitude decrease. The effect of eye position was tested with a repeated-measures ANOVA on the amplitude changes with the factors adaptation position and test position. In case of an eye position-dependent amplitude change, the strongest adaptation is expected at the adapted position. Therefore, an interaction between the factors adaptation position and test position is expected.

RESULTS

We measured the influence of initial eye position on the amplitude change in saccadic adaptation. A saccade of a certain starting position and amplitude was adapted, and adaptation was tested at other initial eye positions in the visual field with an identical retinal saccade vector.

Horizontal arrangement of test positions. To search for an eye position effect on saccadic adaptation we compared the amplitude change arising at the adaptation position with the amplitude change at the other test positions. The average saccade latency was 156 ± 34 ms. The preadaptation amplitudes at the five test positions ranged between 6.57° and 6.72°.

Figure 2*A* shows saccadic amplitudes over the course of one adaptation session of one subject. Adaptation took place at the leftmost fixation position (*position 1*; dark gray dots). The different test positions are grayscale coded. In the preadaptation phase, saccadic amplitudes are clustered together at 6° for all test positions. In the adaptation phase, saccades from fixation *position 1* were adapted and saccade amplitude gradually decreased from 6° to 5°. Only the adaptation trials are shown in Fig. 2*A*; balancing trials are omitted for clarity. In the postadaptation phase, amplitudes of test saccades from all five starting positions are shown (interleaved adaptation trials are omitted). Saccades in test trials from the adapted position remain adapted. Saccades from unadapted initial eye positions showed much less adaptation.

The amount of adaptation, i.e., the amplitude change for the five positions, is shown in Fig. 2*B*. It is calculated as the difference of the averaged preadaptation and postadaptation amplitudes at each position. The amplitude change is highest at the adapted position and lower at the other test positions.

Figure 3 shows the data averaged over all subjects and for all adaptation sessions. Each panel corresponds to a particular adaptation position and depicts the amplitude change at this and the other four test positions.

The amount of adaptation at the adapted positions is of comparable size in all sessions [ANOVA: $F(4,20) = 1.4$, $P = 0.27$]. The amount of adaptation at the nonadapted test posi-

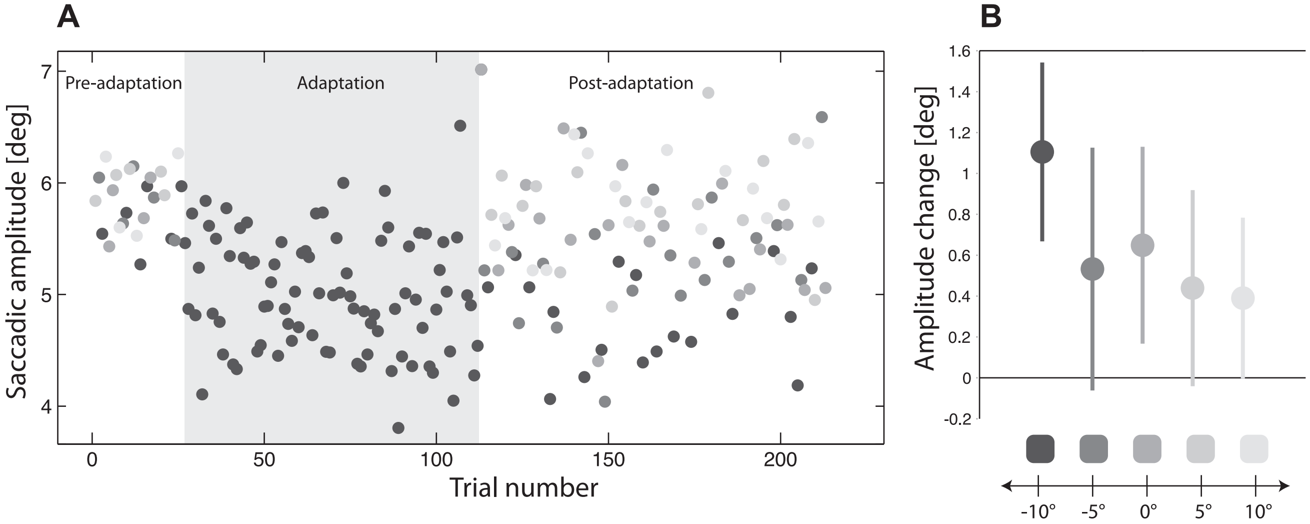

Fig. 2. Single-subject data of an example session of adaptation at the leftmost eye position. The brightness codes the different test positions. Light gray codes the right and dark gray the left positions. The darkest gray codes the adaptation position. *A*: development of the saccade amplitude over the course of the session. Each dot gives the saccade amplitude of 1 trial. In the preadaptation phase the amplitudes are comparable at all test positions. In the adaptation phase, the amplitudes of saccades starting at the leftmost eye position decrease. Data points in the postadaptation phase show the amplitudes of saccades at the different test positions. The amplitudes of saccades starting at eye positions on the left (dark gray) remain reduced, whereas saccades starting at eye positions on the right (light gray) show less adaptation. *B*: means and standard deviations of amplitude changes at the 5 test positions. The amount of adaptation decreased from left to right.

tions, however, clearly shows a strong variation for some adaptation positions (e.g., Fig. 3, *A*, *B*, and *E*). At other adaptation positions (e.g., Fig. 3*C*) the amount of adaptation generalizes well to nonadapted test positions. A two-factor ANOVA with the factors adaptation position and test position gave a significant interaction between the two factors [$F(16,80) = 8.55$, $P < 0.001$], supporting the above observation. There was no significant main effect for adaptation position [$F(4,20) = 1.29$, $P = 0.3$]. Thus the eye position dependencies did not arise from unequal overall adaptation in the different sessions. Asterisks in Fig. 3, *A*–*E*, depict the significant differences in pairwise *t*-tests of the adaptation position with the test positions. The significance level was $P <$ 0.05 uncorrected.

To further quantify the strength of the eye position dependence in each adaptation session we considered linear fits of

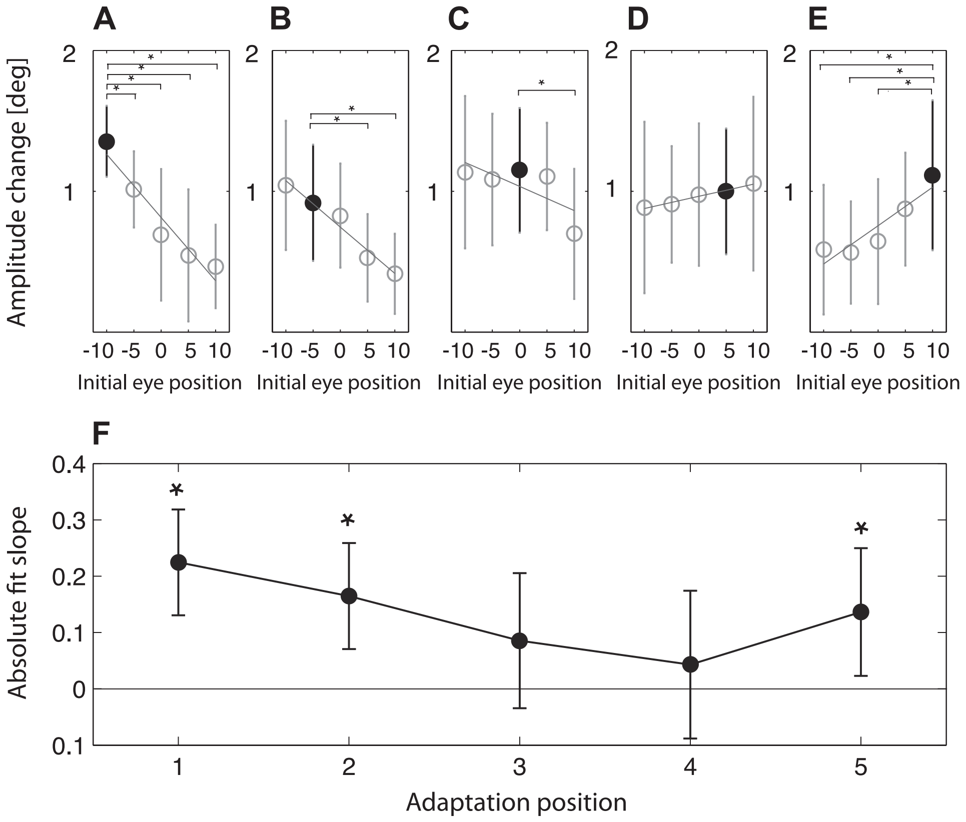

Fig. 3. Averaged amplitude changes for the horizontal arrangement of the different test positions. *A*–*E*: each panel shows the amplitude changes for 1 adaptation session. Filled symbols show the adapted position in each session. A clear dependence of the amplitude change on the eye position is visible at the eccentric adaptation positions −10°, −5°, and 10°. *Significant differences in pairwise *t*-tests of the adaptation position with the test positions (significance level $P < 0.05$ uncorrected). *F*: absolute slopes of the linear fits to the eye position dependence. Error bars show 95% confidence intervals of the fit parameter slope. *Slope values significantly different from zero (α level: 0.05).

the amplitude change data. For each adaptation position the whole data set with all single subject data is included in a linear fit. In Fig. 3, *A*–*E*, the averaged linear fits are shown by lines for each adaptation session. For the left adaptation positions the slopes are negative, whereas for the right adaptation positions the slopes are positive. Slopes are steep at the eccentric adaptation positions −10°, −5°, and 10° (Fig. 3, *A*, *B*, and *E*) and shallow for positions 0° and 5° (Fig. 3, *C* and *D*). In Fig. 3*F* the absolute values of the slopes are shown for the five adaptation positions with their 95% confidence intervals derived from the fit. The slopes at positions −10°, −5°, and 10° are significantly different from zero. This increased influence of eye position for more eccentric adaptation positions becomes evident in the curved shape of the slope plot in Fig. 3*F*. In Fig. 4 the single-subject data are depicted for all sessions.

Furthermore, the curve describing the amplitude change slopes of the five adaptation sessions is shifted to the right, i.e., the left adaptation positions produce a stronger slope than corresponding right positions, producing a bias such that the shallowest slope is found somewhat to the right of the straight-ahead direction. This bias is unexpected because the arrangement of test positions was symmetrical with respect to straight ahead, i.e., the initial eye positions −10° and −5° (Fig. 3, *A* and *B*) have the same eccentricities as initial eye positions 10° and 5° (Fig. 3, *E* and *D*). However, because only rightward saccades were used in our experiment, asymmetries with respect to the central initial eye position in the horizontal arrangement can possibly be related to the saccade direction. For example, an asymmetry in the eye position would arise if the landing position rather than the starting position of the saccade is important for adaptation. This might appear sensible since the error that drives saccadic adaptation is only available after the saccade, i.e., at the saccade landing position. However, if this were the case, then for 7° rightward saccades the relevant positions would all be shifted 7° to the right, effectively increasing the bias rather than eliminating it. Another possible source of the asymmetry in amplitude change transfer could originate from differences between centrifugal and centripetal saccades. When assuming equal amounts of adaptation at the adapted positions, a stronger amplitude change transfer for centrifugal adapted saccades would lead to a higher net amplitude change for the more left test positions. Indeed, the two-factor ANOVA showed such a main effect of the test position [$F(4, 20) = 3.42$, $P = 0.03$]. Therefore, the bias in amplitude change transfer can be explained if centrifugal saccades show stronger transfer than centripetal saccades.

Vertical arrangement of test positions. In the above-described experiment, both the monotonous dependence of gain

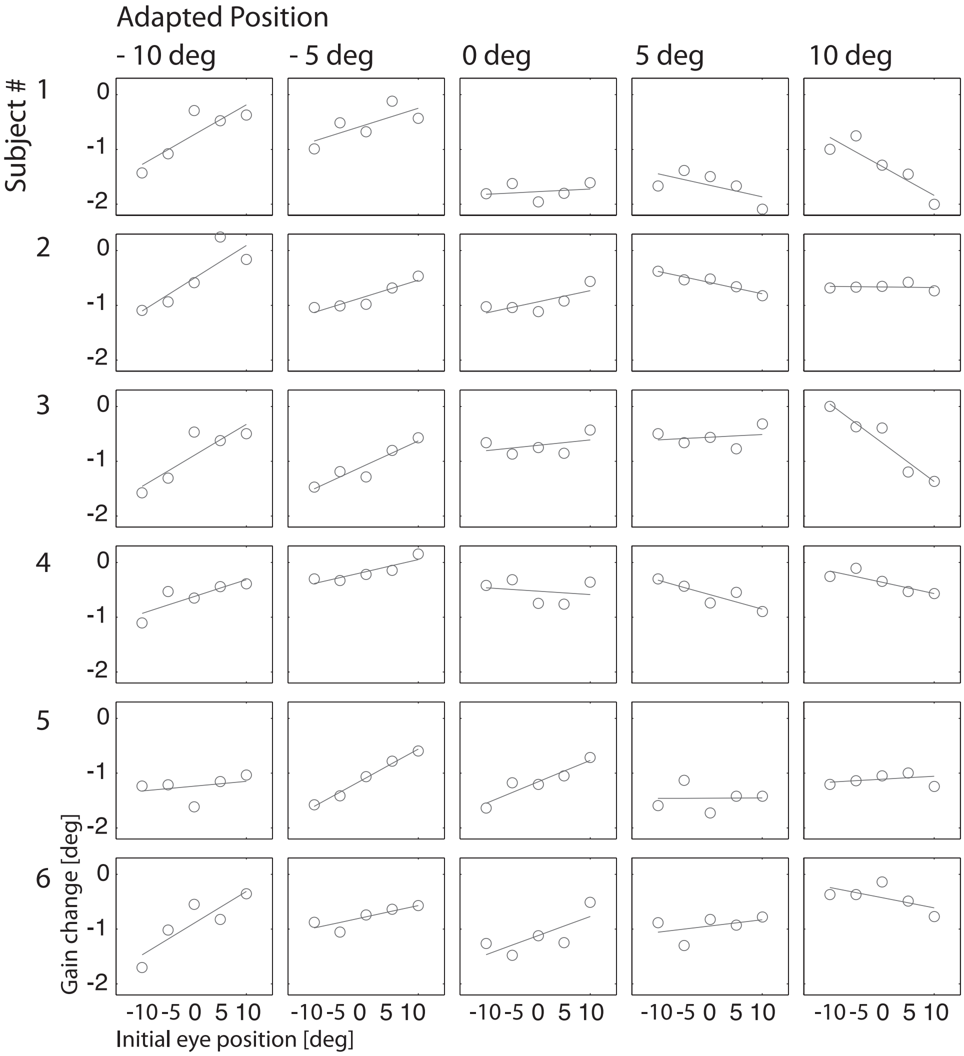

Fig. 4. Single-subject data from the horizontal arrangement of initial eye positions. Each panel represents the amplitude changes of 1 experimental session. From *left* to *right* the adapted position changes; in each line data from 1 subject are shown. Circles show the amplitude changes; the line shows a linear fit.

transfer on horizontal eye position and the rightward bias may be related to the saccade direction, which was horizontal and thus aligned with the test position arrangement. To test whether the alignment of eye position and the saccade vector is responsible for the eye position dependence of saccadic adaptation, we conducted an experiment in which eye position was varied vertically but the saccade direction remained horizontal. The preadaptation amplitudes at the five initial eye positions ranged between 6.45° and 6.66°. Average saccade latency was 158 ± 36 ms.

Figure 5, *A–E*, shows the spatial amplitude change profiles for the five adaptation sessions averaged over subjects (individual data in Fig. 6). The adaptation reached at the adapted positions was not significantly different between the sessions [ANOVA: $F(4,16) = 0.99$, $P = 0.44$]. A two-factor ANOVA of amplitude changes showed no significant main effects for adaptation position [$F(4,16) = 2.43$, $P = 0.09$] or for test position [$F(4, 16) = 1.21$, $P = 0.3$], indicating comparable average adaptation in all sessions and no bias in the test positions. As for the horizontal arrangement there was a significant interaction between adaptation position and test position [$F(16,64) = 4.56$, $P < 0.001$]. The significant pairwise comparisons of the adaptation position with the test positions in each session at a significance level of $P < 0.05$ are marked by asterisks in Fig. 5, *A–E*. The linear fits are superimposed. The slope values are shown in Fig. 5*F*. As for the horizontal arrangement of initial position, the dependence of adaptation transfer on eye positions was strong in the most eccentric adaptation positions and shallow for the more central adaptation positions.

We conclude that the transfer of amplitude change depended on eye position also for vertical eye positions saccades. Analogous to the horizontal arrangement of initial eye positions, the amplitude change transfer was modulated more strongly by eye position for more eccentric adaptation positions, resulting in steeper slopes. These findings are similar to those for the horizontal arrangement, suggesting that the eye position dependence is not due to an alignment between saccade vector and the direction of initial eye position variation. Moreover, this result also shows that the eye position effect in general is not explained by differences between centripetal and centrifugal saccades, because the saccades are all centrifugal in the vertical arrangement of eye positions.

Durations and peak velocities. Changes in saccadic amplitude are usually accompanied by changes in saccade metrics. Ethier et al. (2008) experimentally compared adapted saccades with unadapted saccades of the same amplitude in a mimic-adaptation session with the same number of trials. The adapted saccades had lower peak velocities and longer durations than the unadapted saccades of the same amplitude. Another comparison is that between the unadapted saccades in the preadaptation trials and the adapted saccades of the postadaptation trials. This comparison involves saccades of different amplitude because amplitude is reduced during adaptation. The model proposed by Ethier et al. (2008) predicts mainly a peak velocity decrease for inward adaptation in this comparison. However, Golla et al. (2008) reported a decrease in both peak velocity and duration during adaptation. Thus the mechanism behind saccadic adaptation may involve adjusting one or both of these saccade control parameters.

We assessed the amount of change in saccade duration and peak velocity between preadaptation and postadaptation trials in each adaptation session to see whether the discrepancies in the amount of adaptation transfer could be seen in different

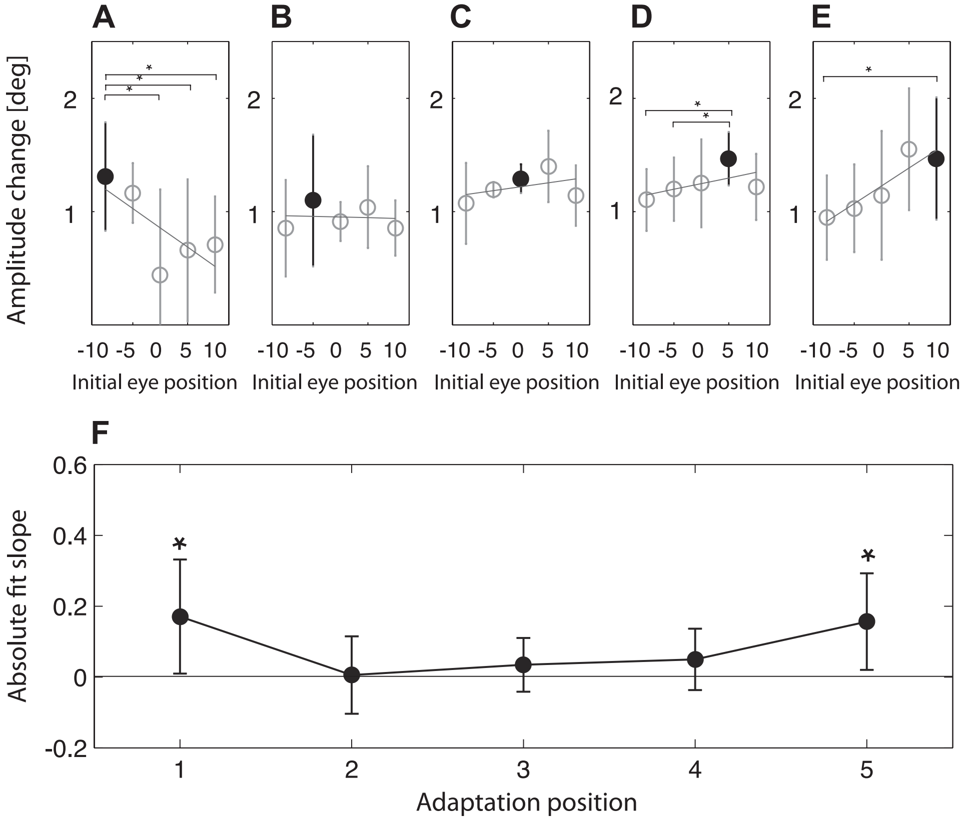

Fig. 5. Averaged amplitude changes for the vertical arrangement of test positions. *A–E*: each amplitude change for each adaptation session. Filled symbols show the adapted position in each session. *Significant differences in pairwise *t*-tests of the adaptation position with the test positions (significance level $P < 0.05$ uncorrected). *F*: means and 95% confidence intervals for the absolute slopes of the linear fits to the eye position dependence. *Slope values significantly different from zero (α level: 0.05).

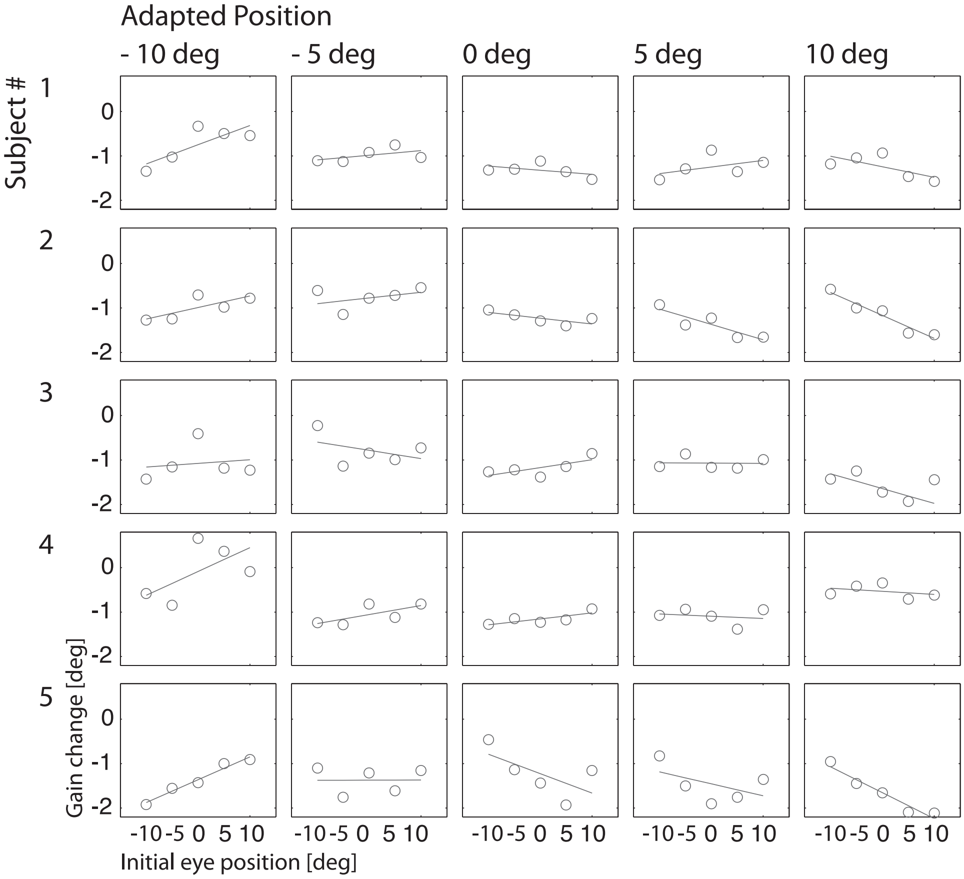

Fig. 6. Single-subject data from the vertical arrangement of initial eye positions. Each panel represents the amplitude changes of 1 experimental session. From *left* to *right* the adapted position changes; in each line data from 1 subject are shown. Circles show the amplitude changes; the line shows a linear fit.

amounts of change in either of these metrics. In accordance with Golla et al. (2008) we found that the modulation with eye position that occurred in the saccade amplitudes was similarly present in durations and peak velocities. Duration and peak velocities decreased significantly during adaptation (peak velocities and durations for both eye position arrangements: $P < 0.0001$), and both decreases were smaller at eye positions at which the amplitude change was smaller. However, a repeated-measures ANOVA showed a significant interaction only for peak velocities [$F(4,20) = 2.28$, $P < 0.01$ in the horizontal experiment; $F(4,16) = 1.98$, $P < 0.05$ in the vertical experiment].

DISCUSSION

To summarize, our results show that eye position can modulate the amplitude change of saccades of a fixed retinal vector after inward adaptation in humans. This modulation was especially prominent at eccentric initial eye positions. The modulation profile was rather flat after adaptation at a central initial eye position. A linear transfer profile described the modulations of gain well. Saccadic gain changes transferred only partially in space for both horizontal and vertical variations of initial eye position. In the horizontal paradigm, a bias in the eye position specificity results in a more pronounced spatial gain change profile for antialignment of retinal target vector and initial eye position vector.

Before we discuss the implications of these results, we should note that our experiments were conducted with reactive saccades that were made in reaction to a suddenly appearing target. Many studies on saccadic adaptation in humans have shown that different categories of saccades (reactive, scanning, overlap, memory guided) have partially different mechanisms of adaptation (Alahyane et al. 2007; Hopp and Fuchs 2004; Panouilleres et al. 2009; Pelisson et al. 2010; Zimmermann and Lappe 2009). Because of these differences between different types of saccades we must be cautious in generalizing our findings to saccades of other categories. Moreover, the present results were achieved with inward adaptation, i.e., the adaptive shortening of saccade amplitude. Several recent observations have suggested that inward and outward adaptation rely on partly different mechanisms (Alahyane et al. 2007; Catz et al. 2008; Ethier et al. 2008; Panouilleres et al. 2009; Zimmermann and Lappe 2009). Eye position modulation occurs also for outward adaptation, but it is smaller for reactive than for scanning saccades (Zimmermann and Lappe 2011).

Thus we begin our discussion by stating that inward adaptation of reactive saccades shows eye position-dependent modulations.

Previous studies involving eye position in saccadic adaptation have used eye position as a contextual cue, showing that saccades at one eye position can be adapted differently from saccades of the same vector at another eye position (Alahyane and Pelisson 2004; Semmlow et al. 1989; Shelhamer and Clendaniel 2002; Tian and Zee 2010; Watanabe et al. 2000). Thus saccadic adaptation can be restricted to only a particular part of space. Our results are consistent with this. However, when two different directions of adaptation at two different eye positions were imposed, it is likely that the competition between these two simultaneous adaptation requirements established the influence of eye position in the adaptation in those studies. Our results show that eye position is an inherent factor in saccadic adaptation even when only a single eye position is used for the adaptation process.

Previous studies that adapted at only one eye position and tested transfer to other eye positions did not reveal eye position effects and concluded that inward reactive adaptation takes place exclusively in a retinotopic frame of reference (Albano 1996; Deubel et al. 1995; Frens and van Opstal 1994; Semmlow et al. 1989). However, two of these studies (Semmlow et al. 1989; Frens and van Opstal 1994) adapted at a central eye position and tested at eccentric eye positions. The lack of eye position modulation in these studies is therefore consistent with our results, which showed strong eye position dependence only for eccentric adaptation positions. Deubel et al. (1995) grouped initial eye positions into centripetal and centrifugal saccades and found complete transfer between these two groups. The adaptation at several initial eye positions might have smeared out the eye position specificity. The study by Albano (1996) is most closely related to ours. Albano also adapted at only one position and tested at two further positions. The adaptation position was either central or eccentric. In neither case did the amplitude change decrease significantly between test and adaptation position. Albano therefore concluded that saccadic adaptation took place in retinocentric, not craniocentric, coordinates. However, the three positions that were tested in that study were 0 and ±3° from straight ahead, and saccade size was only 3°. Therefore, because all included eye positions were close to central the eye position dependence might not have been strong enough to be observable.

These considerations lead to the question of how spatial transfer of adaptation can be restricted to the central region.

When considering eye position in saccadic adaptation, most approaches have expressed eye position as context. One possibility to include eye position contexts in the mechanism of saccadic adaptation is an eye position-dependent modulation in a retinocentric reference frame (Fig. 7). Consider that neurons in many parts of the saccade circuitry encode space in a retinocentric reference frame and that the activity of these neuron is modulated by eye position gain fields of the kind implicated in monkey electrophysiology (Andersen and Mountcastle 1983; Campos et al. 2006; Cassanello and Ferrera 2007; van Opstal et al. 1995; Zipser and Andersen 1988) and human imaging studies (Brotchie et al. 2003). Then, for a given motor vector, different neuronal subpopulations exist that fire more strongly for left or for right eye positions, respectively. Figure 7 depicts at the target representation stage a neuron pool preferring left eye positions and a neuron pool preferring right eye positions.

Depending on the initial eye position during adaptation, the two populations contribute differently to the generation of the saccade. For example, when adapting at a left eccentric position, the neurons firing more strongly for the left eye position contribute more to the saccadic drive. If the activity of neurons with stronger saccade-related responses weighs more on the effects of adaptation, then mostly the left-preferring subpopulation contributes to the adaptation, as shown by the size of the arrows to the adaptation stage in Fig. 7. Saccades starting at right initial eye positions are driven mostly by the neuron pool preferring right eye positions, which is not adapted because it contributed little to the saccades originating from the adapted location. Therefore the amount of amplitude change will depend on initial eye position. However, when adapting at a central position, both subpopulations fire at intermediate rates and both contribute to the saccade generation. Therefore, all neurons contribute to the adaptation and the amplitude change is seen at all eye positions.

This scheme is able to produce the eye position modulations at eccentric adaptations and the full transfer at central adaptation. It only assumes that the saccade target information is coded as an implicit spatial representation in a combination of a retinotopic motor vector coding with eye position gain fields and that only those neurons contribute to adaptation that fire strongly for the saccade that is adapted. Moreover, this scheme

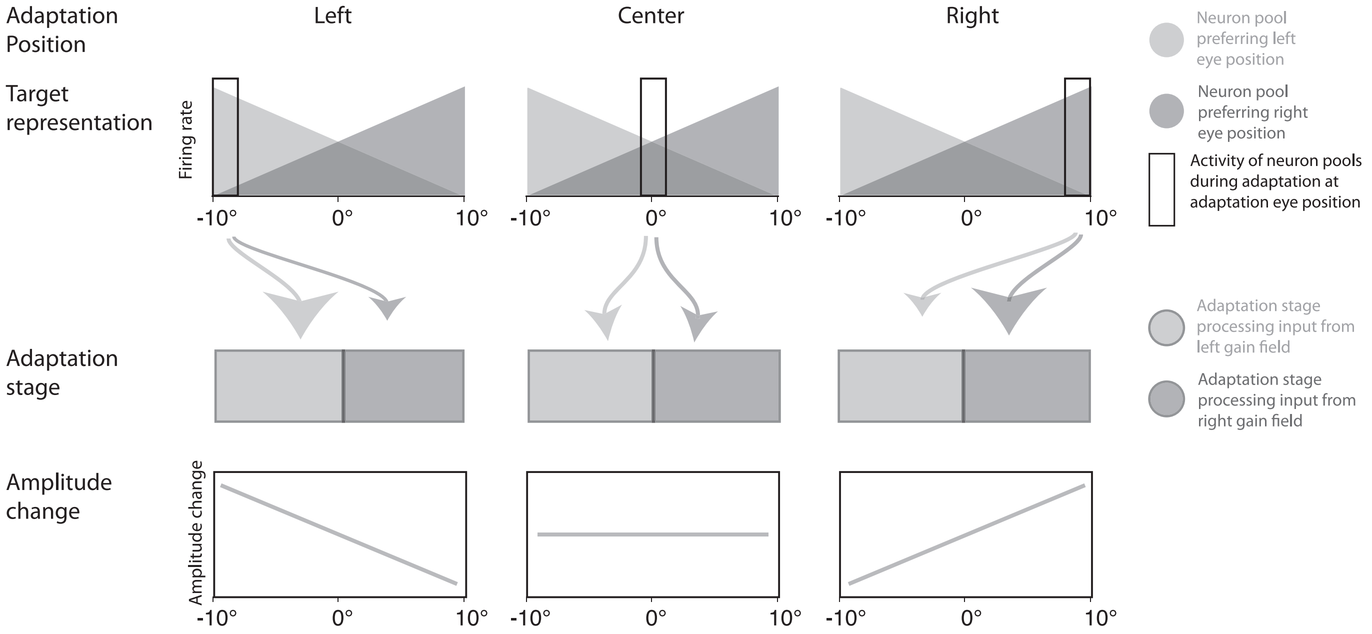

Fig. 7. Sketch of a possible mechanism for the eye position dependent modulation of saccadic adaptation. See DISCUSSION for explanation.

would accommodate the results of experiments that adapted saccades from two different eye positions since the two positions would be driven by different subpopulations of neurons and hence can provide different adaptation states.

The scheme would work either for a motor vector command or for a gaze shift command of a combined eye and head movement (Freedman and Sparks 1997; Munoz et al. 1991), provided that the population of neurons that contribute to either command contains eye position gain fields.

The adaptation data along the horizontal axis showed a bias such that the shallowest slope is found somewhat to the right rather than in the straight-ahead direction. Such a bias could be formed in the above model if the gain field direction is linked with the saccade direction. This produces an unequal population size for left and right eccentricity. Specifically, if a higher proportion of neurons have a gain field oriented against the saccade direction than in the saccade direction, then stronger adaptation rates and steeper transfer profiles are expected in the contraversive hemifield, consistent with the observed bias. Although many cortical areas feature an equal distribution of gain field directions (Bremmer et al. 1997a, 1997b) the gain fields, for example, in the FEF show such an anticorrelation with the preferred saccadic vector (Cassanello and Ferrera 2007).

The cerebellum plays a central role in saccadic adaptation (Catz et al. 2008; Golla et al. 2008; Inaba et al. 2003; Optican and Robinson 1980). The involvement of higher stages of oculomotor control is controversial. Many detailed properties of the adaptation of different types of saccades in humans suggest that areas above or at the level of the SC are involved in saccadic adaptation (overview in Hopp and Fuchs 2004; Pelisson et al. 2010). Physiological studies in monkeys, however, saw no evidence for adaptation in the collicular map (Edelman and Goldberg 2002; Frens and van Opstal 1997; Melis and van Gisbergen 1996; Quessy et al. 2010) but only mild changes in the firing rates (Takeichi et al. 2007). Retinotopic encoding of the saccade vector along with an eye position gain field is a common finding in much of the circuitry that generates a saccade [fastigial nucleus (Fuchs et al. 1993), NRTP (Crandall and Keller 1985), SC (Campos et al. 2006; van Opstal et al. 1995), LIP (Andersen et al. 1990), and FEF (Cassanello and Ferrera 2007)]. However, the model suggested above does not require that adaptation take place in these areas. Instead, it would be sufficient that the target command coming from areas such as SC, LIP, or FEF and providing input to the adaptive circuitry in the cerebellum contains a gain field modulation. If the cerebellum keeps track of its inputs and modifies saccade amplitude only for active inputs, as suggested by Edelman and Goldberg (2002), then only saccades at the adapted position will be affected.

This scenario leaves two possibilities for the properties of single Purkinje cells in the cerebellum. First, single Purkinje cells may show eye position gain fields, and the contribution of a Purkinje cell to adaptation may be proportional to the strength of its eye position tuning. Alternatively, each Purkinje cells may receive input from neurons of all different eye positions gain fields, and the net eye position effect may be balanced out such that the neuron might not show a gain field for unadapted saccades. In this case, however, as synaptic input strength changes during adaptation, the neuron should develop a gain field over the course of adaptation. Both possibilities may be tested experimentally in single-neuron recordings.

GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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