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RESEARCH ARTICLE

Control of Movement

Eyeball translations affect saccadic eye movements beyond brainstem control

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Abstract

Vision requires that we rotate our eyes frequently to look at informative structures in the scene. Eye movements are planned by the brain but their execution depends on the mechanical properties of the oculomotor plant, that is, the arrangement of eyeball position, muscle insertions, and pulley locations. Therefore, the biomechanics of rotations is sensitive to eyeball translation because it changes muscle levers. Eyeball translations are little researched as they are difficult to measure with conventional techniques. Here, we investigated the effects of eyeball translation on the coordination of eyeball rotation by high-speed MRI recordings of saccadic eye movements during blinks, which are known to produce strong translations. We found that saccades during blinks massively overshoot their targets and that these overshoots occur in a transient fashion such that the gaze is back on target at the time the blink ends. These dynamic overshoots were tightly coupled to the eyeball translation, both in time and in size. Saccades made without blinks were also accompanied by small amounts of transient eyeball retraction, the size of which scaled with saccade amplitude. These findings demonstrate a complex combination of rotation and translation of the eye. The mechanical consequences of eyeball translation on oculomotor control should be considered along with the neural implementation in the brainstem to understand the generation of eye movements and their disorders.

NEW & NOTEWORTHY We found that saccades during blinks can massively overshoot their target when the eyeball is retracted. Our data imply that the overshoots are not part of the saccade plan prepared in the brainstem, but instead a consequence of the altered biomechanics resulting from concurrent eyeball translation and rotation. To our best knowledge, this is the first direct observation of dynamic properties of the oculomotor plant altering the execution of rotational eye movements.

blink; eye movement; MRI; saccade

INTRODUCTION

Saccades are the most frequent movements we make and are orchestrated in detail by dedicated brainstem circuitry (1). They are driven by a pulse activity, a brief burst of action potentials to the agonist rectus muscle combined with simultaneous inhibition of activation in the antagonist muscle to produce rotational eye acceleration. Then, neural activity is reduced to an appropriate level to keep the eye steady at the desired orientation. Anatomical studies showed that each eye muscle has a connective tissue pulley that acts as a lever in close proximity to the eyeball (2, 3). Small changes in eyeball position or pulley location, therefore, have consequences for the biomechanics of rotational eye movements by changing the muscle levers. For example, orientation-dependent pulley locations have been proposed as a mechanical implementation of Listing's law (4), which prescribes torsional rotation as a function of eye orientation (5). The pulleys of the horizontal rectus muscles are located only around 8 mm posterior to the orbital center, implying that even 1–2 mm of eyeball translation might be sufficient to have large implications on the kinematics of horizontal eye movements.

A strong posterior translation (retraction) of the eye occurs in conjunction with blinks. During a blink, the extraocular muscles simultaneously co-contract so that the eyeball as a whole is being lifted and retracted back into its socket (6). Interestingly, other subsystems of oculomotor control are still able to operate while the eye is retracted. It has been shown that the period of eye occlusion during the blink can be used to correct fixation errors (7), move gaze to target (8),

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reset torsion (9), and elicit saccades (10, 11). The interaction between the blink and the saccade systems in the brainstem has received particular interest (12–14), in part because omnipause neurons in the pons are inhibited during blinks (15) and also play a crucial role in the saccade premotor circuit. Saccades that are made together with blinks are closely time-locked to blink onset and also slower than those without blinks (10, 11, 16, 17). These altered saccade kinematics might be due to an interaction of blink and saccade systems in the brainstem or they could result from mechanical interference of the eyeball translation and the change in muscle levers. Observations of dynamic saccade overshoots during blinks (10, 17) hint at a mechanical contribution to the kinematics of within-blink saccades. Eyeball translation during blinks might affect the lever arm of the rectus muscles in such a way that a saccade that is planned properly by the brainstem is deflected while the eye is retracted, thus producing a transient overshoot.

Dynamic properties of the oculomotor plant, like eyeball translation, are difficult to investigate with conventional eye-tracking techniques. Recent advances in high-speed magnetic resonance imaging (MRI) allow obtaining anatomical image sequences of the eyes with sufficient spatiotemporal resolution to resolve saccadic eye movements. We used MREyeTrack, an eye-tracking method allowing measurement of the kinematics of eye movements in terms of both translation and rotation by segmenting sclera, lens, and cornea in each image (18). Axial single-slice MRI data were acquired at a temporal resolution of 55.6 ms of both eyes from eight participants, who were instructed to make saccades with and without blinks. We aimed to study the relationship between eyeball retraction and the saccade trajectory, with a particular focus on investigating whether dynamic overshoots of within-blink saccades could be caused by eyeball retraction.

METHODS

Participants

Eleven healthy participants (*P1–P11*, age 23–49, 1 female, 10 males) participated in this study and gave written informed consent. Since the experiment examines the basic movement of the eyeball, we did not expect a gender dependence and did not prioritize gender balance in the participant pool. All procedures were approved by the ethics committee of the Department of Psychology and Sports Science of the University of Münster. The same participants took part in another study from our laboratory with an identical experimental setup, but a different experimental protocol and study goal (6).

Experimental Setup

Eye movements were recorded in the axial plane at a temporal resolution of 55.6 ms using a 3 T Philips Achieva Scanner (Philips Medical Systems, Best, The Netherlands) and a balanced steady-state free precession (bSSFP) MRI sequence. Participants laid supine in the scanner and could see stimuli & instructions on a back-projection monitor that was placed at a total viewing distance of 108 cm. Before collecting dynamic single-slice data, we started the experiment with the acquisition of static three-dimensional (3-D) T2 weighted data of the entire head (matrix = 256 × 256 × 250, FOV = 250 × 250 × 250 mm, voxel size = 0.98 × 0.98 × 1.00 mm, TE = 225 ms, TR = 2500 ms, slice thickness = 2 mm, flip angle = 90°, scan duration = 232.5 s), during which the participants were instructed to fixate a dot in the center of the screen. The 3-D data were used as a reference for planning the dynamic single-slice data acquisition and to obtain precise knowledge of the eyeball of each participant, which was used later on in the data analysis. Eye movements were then recorded at a temporal resolution of 55.6 ms using a bSSFP sequence in the axial plane (matrix = 224 × 224, FOV = 200 × 200, voxel size = 0.89 × 0.89 mm, TE = 1.28 ms, TR = 2.56 ms, slice thickness = 3 mm, flip angle = 45°, 1,020 dynamic scans, total scan duration = 56.7 s). To capture eye movements at the highest possible temporal resolution, we used k-t BLAST, a dedicated technique to accelerate image acquisition by reducing the amount of acquired k-space data by a given factor but largely preserving image quality by incorporating prior information of the object being imaged (19). We chose a k-t BLAST acceleration factor of 5.

Experimental Protocol

Our goal was to collect horizontal saccades of various amplitudes, in both directions, with and without blinks. Therefore, participants were instructed to continuously look back and forth between two targets along the horizontal meridian. We collected data in six separate sessions, with target positions either at ±2.5°, ±5°, or ±10° and the instruction to make the saccades either with or without blinking. In between sessions, which lasted for 56.7 s each, we monitored that the lens was fully visible and adjusted the slice position if necessary. Targets were black dots of 0.8° diameter on a gray background. We used MATLAB (The MathWorks, Natick, MA) with the Psychophysics Toolbox (20) for stimulus presentation.

Data Analysis

Preprocessing.

We estimated global head motion in the dynamic bSSFP scans using an efficient subpixel image registration by cross-correlation algorithm (21). The coarse location of the eyeball was then identified using the fast-radial symmetry transform (22) and the MR data was cropped around it for further analysis. For better comparison across individual scans and participants, we rescaled the image intensities such that the mean intensity around the eyeball center had a value of 1 for each image.

Eye tracking.

Orientation of the eyeball in the horizontal plane and position of the eyeball along the anterior-posterior axis were quantified for both eyes in each image using the MREyeTrack algorithm (18) with minor modifications (6). The algorithm segments sclera, lens, and cornea in the dynamic MR data by matching the projection of a 3-D eyeball model obtained from the static 3-D MR data of each participant. Therefore, orientation and position are always in reference to the fixation of a target dot in the center of the screen. For further analysis, we interpolated all eye motion data to a 2-ms time interval and then

smoothed the data using a Savitzky-Golay filter of second-order (polynomial) order and 100-ms window length (23). This has the advantage of analytically obtaining derivatives that are used later on to choose velocity threshold for on- and offset detection. We chose order and window length conservatively to stay as close as possible to the raw data points, as shown in the Supplemental Material (Supplemental Fig. S1; all Supplemental material is available at https://doi.org/10.6084/m9.figshare.c.6163152.v3).

A note on terminology. In the literature, eye position is often used to describe the direction in which the line of sight is pointing. In the present paper, we use eye position as a description of the position of the eyeball in the orbit. We use orientation to describe the direction in which the optical axis is pointing in the orbit and rotation for the change of orientation. We use position for the position of the eye in the orbit and translation for the change in position, retraction for translation toward the back of the orbit. We use gaze whenever we want to relate the eye orientation to a target in the visual scene.

Saccade detection.

Saccades between the two targets were identified using a velocity threshold. If the gaze trajectory passed the midline at a velocity of at least 30°/s this was considered to be part of a saccadic eye movement. On- and offset were then defined as the samples where the velocity fell below 10°/s. Some of the saccades elicited while blinking had dynamic overshoots, which are characterized by a rotation temporarily exceeding the target eccentricity followed immediately by a transient return motion in the opposite direction. Typically, saccade kinematics are described by their amplitude (eye orientation difference between on- and offset), duration, and peak velocity. To analyze the kinematics of saccades with dynamic overshoots we additionally recorded their maximum excursion (the maximum eye orientation during the saccade), overshoot (the difference in eye orientation between maximum excursion and orientation after saccade offset), and return (when eye orientation was halfway between overshoot and final orientation).

Blink detection.

Since we did not have data on eyelid motion we used eye motion data as a proxy for blink detection. Earlier work on MREyeTrack with coregistered video eye tracking showed that blinks appear as Gaussian-like peaks in the eye retraction data so that the retraction velocity profile of each blink is characterized by a positive peak for lid closure and a negative peak for lid opening (18). Following the results from that paper we applied a velocity threshold of 1 mm/s to determine on- and offset and further required valid blinks to have a duration of eyeball retraction longer than 100 ms and a maximum retraction greater than 0.3 mm. The kinematics of the retraction were further characterized by their amplitude, the maximum amount of retraction, and their time of return, which was the point in time at which the retraction was halfway between its maximum position and eye position at the end of the saccade.

Data exclusion criteria.

Precise eye motion estimation relies on high-quality MR images and full visibility of the lens and cornea. Even though we corrected the slice position for occasional head motion between runs, out-of-plane head motion within a run could move the lens out of the image. The anterior segment of the eye is also especially sensitive to susceptibility artifacts, which stem from local magnetic field distortions at the interface of air and tissue. If the lens or cornea is not well visible, either due to susceptibility artifacts or out-of-plane head motion, this manifests itself as a lower energy functional in the MREyeTrack algorithm. We found that the data quality of participants having mean energy functionals below 1.5 for either sclera, lens, or cornea was not suitable for accurate motion analysis. Looking at mean energy functionals of the sclera, lens, and cornea across all sessions for each participant (Supplemental Table S1), this excluded the data of participants *P1*, *P3*, and *P4* from further analysis.

RESULTS

In three sessions of dynamic MR data acquisition, we presented two visual targets along the horizontal meridian at a distance of 5°, 10°, and 20° from each other. Participants were instructed to continuously look back and forth between the two visual targets (Supplemental Movie S1). Then, we collected another three sessions with identical stimuli but this time instructed participants to make the gaze shift while blinking. To determine the precision with which the MREyeTrack algorithm (Fig. 1*A*) is able to estimate eye orientation in our experimental setup, we compared frame-by-frame estimations of eye orientation between left and right eye across the entire data set. Because the eye movements are conjugate but each is determined independently by MREyeTrack, comparing the measurements between the two eyes indicates the variability, respectively the precision, of MREyeTrack. As expected, horizontal eye orientation was highly correlated between the left and right eye (Pearson's $r \geq 0.95$ and $P < 0.001$) for all participants (Fig. 1*B*). The residuals from linear regression analysis had a mean standard deviation of 1.3°. Information on the accuracy of MREyeTrack in estimating saccade amplitude has been obtained previously by comparison with simultaneous video-based eye tracking (18).

Dynamic Overshoots of Within-Blink Saccades

Saccades that are elicited within a blink sometimes show large dynamic overshoots in which the eye orientation far exceeds the target eccentricity but returns to the target before the lid opens again (Fig. 2*A* and Supplemental Movie S2). Dynamic overshoots can reach several degrees of visual angle in size and occur right in the middle of a blink while the eye is retracted. To collect within-blink saccades of varying amplitude and direction, we instructed participants to shift their gaze, while voluntarily blinking, between targets at 5°, 10°, and 20° distances from each other. The occurrence of dynamic overshoots among the within-blink saccades was highly variable across saccade amplitudes and directions as well as across participants (Fig. 2*B*). Although the within-blink saccades of one-half of the participants (*P5*, *P8*, *P9*, and *P10*) showed barely any dynamic overshoots, the other half (*P2*, *P6*, *P7*, and *P11*) made them frequently. Their frequency of occurrence did not show any recognizable pattern with regard to saccade amplitude or direction. The size of dynamic

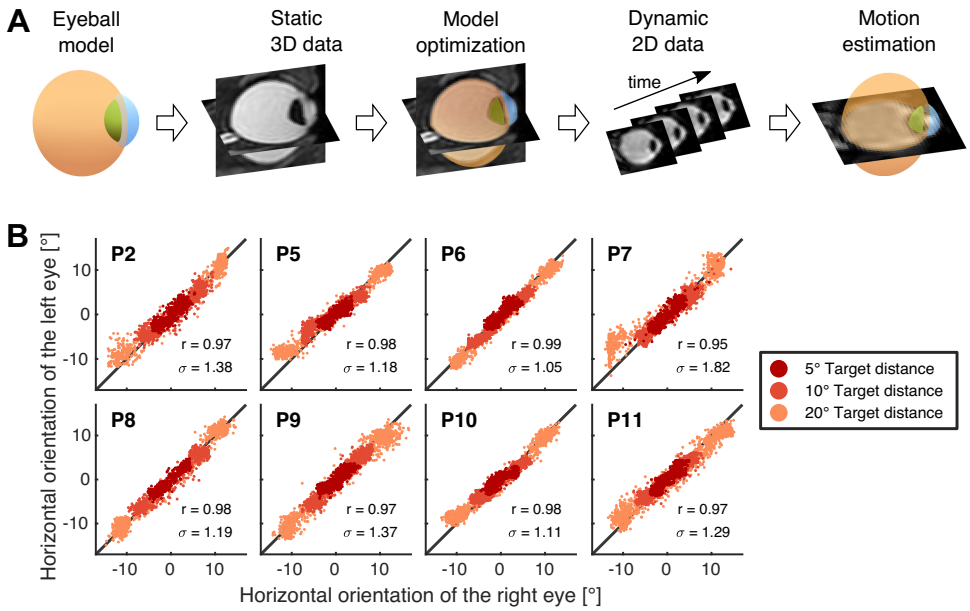

Figure 1. Eye motion estimation using MREyeTrack. *A*: illustration of the MREyeTrack workflow. The eyeball is modeled as a combination of three ellipsoids representing the sclera, lens, and cornea and subsequently optimized to the individual three-dimensional (3-D) MR data of each participant. Eye motion in the dynamic two-dimensional (2-D) MR data is then estimated by finding the optimal projection of the 3-D eyeball model. Reproduced from Kirchner et al. (18) under Creative Commons Attribution CC-BY 4.0. *B*: precision of MREyeTrack's estimation of eye orientation assessed frame-by-frame by comparing left and right eye orientation while the participants made conjugate eye movements back and forth (without blinking) between targets at three different distances. Pearson's *r* of the linear regression (all $P < 0.001$) and standard deviation σ of the residuals are given for each participant.

overshoots also varied across participants and saccade properties (Fig. 2*C*). It should be noted that subtle overshoots, particularly those associated with 5° saccades, might have been missed in the present study due to low sampling rate. This study focuses on strong overshoots of several degrees in visual angles in combination with eyeball retraction, which necessitates the use of dynamic MRI.

Binocular Comparison of Maximum Excursion during Dynamic Overshoots

The MRI recordings showed that dynamic overshoots occurred in both eyes with only little difference in maximum excursion (Fig. 3*A* and Supplemental Movie S3). We compared the maximum excursion between right and left eye for all within-blink saccades exhibiting a dynamic overshoot. These measures were highly correlated (Pearson's $r = 0.98$, $P < 0.001$, Fig. 3*B*). The linear regression had an intercept of −1.8°, suggesting a directional bias not necessarily related to the saccade itself. Instead, it might reflect the rotational trajectory of the blink-related eye movement (BREM), which is superimposed on all of the saccadic eye movements. The blink-related eye movement, albeit small, is of opposite sign for the two eyes and might therefore be responsible for the intercept. We measured blink-related eye movements for each eye in an earlier study with the same participants (6). From this data, we calculated an averaged template from blinks without saccades and subtracted this template from the within-blink saccade data of

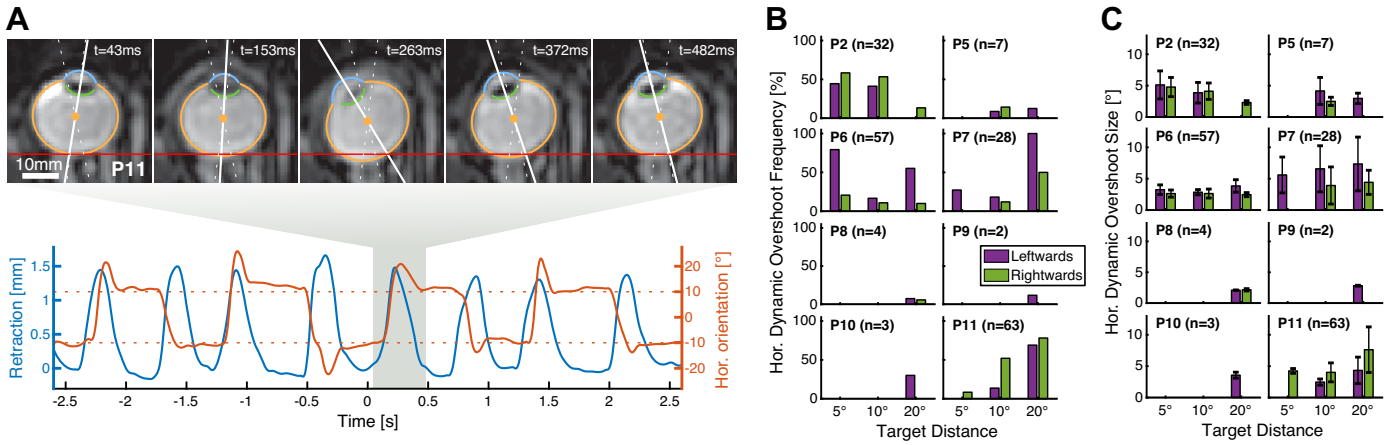

Figure 2. Dynamic overshoots of within-blink saccades. *A*: time series of horizontal eyeball orientation and retraction from eight blinks, which can be identified by the Gaussian-like peaks in the retraction data. Participants were instructed to shift their gaze between targets at ±10° (dotted horizontal lines) while blinking. These within-blink saccades often exhibited a dynamic overshoot. This is highlighted by the five magnetic resonance images of one particular blink which show that eye orientation (solid white line) far exceeds the visual target eccentricity (dotted white line) in the middle of the blink before returning to the target toward the end of the blink. Time is relative to onset of the highlighted blink. The location of the posterior eyeball border in the first image is marked in each image as a horizontal red line to illustrate the amount of retraction during a blink. *B*: frequency of dynamic overshoot occurrence from all within-blink saccades grouped into left- and rightward saccades as well as target distance. *C*: same for the average size of the dynamic overshoots. Error bars are standard deviation.

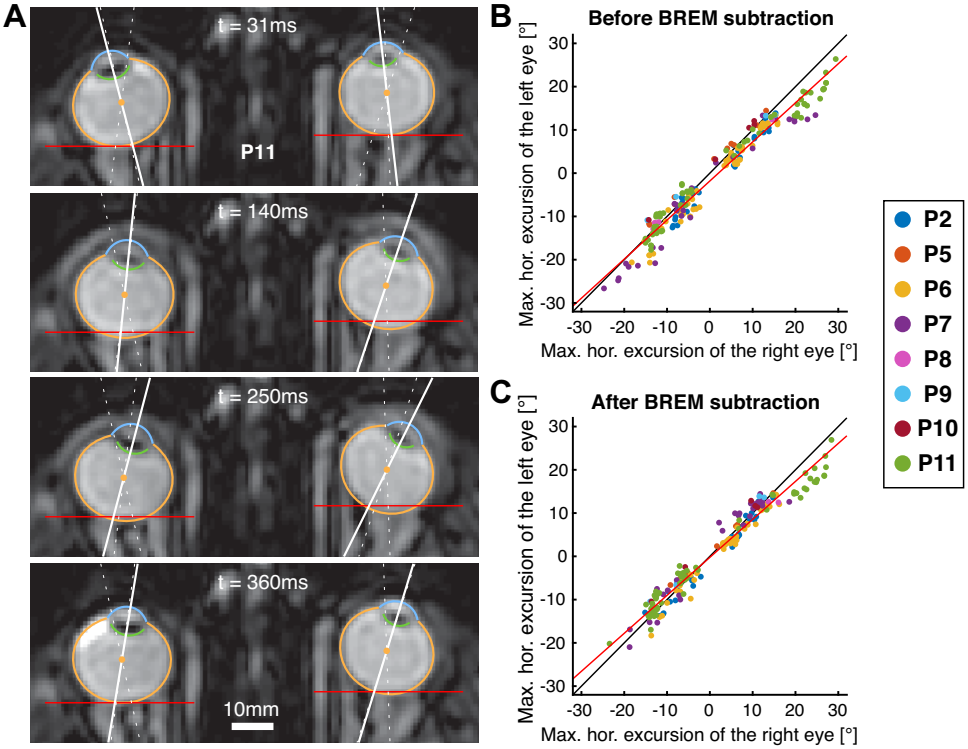

Figure 3. Excursion during dynamic overshoots is similar in both eyes. *A*: example of a leftward within-blink saccade with a dynamic overshoot. The third image from top shows the orientation (solid white line) of both eyes moving beyond the target eccentricity (dotted white line) before returning to the target in the fourth image. The location of the posterior eyeball border in the first image is marked in each image as a horizontal red line to illustrate the amount of retraction during a blink. Time is relative to blink onset. *B*: comparison of maximum excursion of eye orientation during dynamic overshoots between left and right eye for all participants (each with a unique color) before subtracting the blink-related eye movement (BREM). Linear regression in red, identity line in black. *C*: after subtraction of the BREM, the intercept of the linear regression is reduced to −0.2° from −1.8°.

each eye. After subtraction, the maximum excursion of the left and right eye was still highly correlated (Pearson's $r = 0.98$, $P < 0.001$) and the intercept was reduced to −0.2° (Fig. 3*C*).

Careful observation of Fig. 3, *B* and *C* also shows that for some subjects maximum excursion differed between leftward and rightward saccades (compare e.g., the dark blue and the purple data points). However, this was not apparent across the population and indicates individual idiosyncrasies in overshoot.

Relationship between Eyeball Retraction and Dynamic Overshoots

Dynamic overshoots may be caused mechanically by eyeball retraction or may be part of the neural signal that forms the saccade command. Crucially, if the saccade overshoot results mechanically from eyeball retraction, this would manifest itself in two ways. First, the overshoot would only occur after the retraction has reached full amplitude and is likely to be in close temporal proximity to the time of maximum retraction. Second, the return phase of the saccade overshoot would be an incidental consequence of the return motion of the retraction and should therefore be tightly time-locked to the retraction return. To quantify these predicted relationships, we determined the temporal characteristics of the blink-induced eyeball retraction. We kept track of the time of maximum retraction and the time of retraction return, which we defined as the return movement reaching half-maximum retraction. Analogously, the temporal characteristics of the eye rotation during the saccade trajectory were determined by overshoot and return, where saccade overshoot refers to the time of maximum excursion and saccade return to the time when the gaze is half-way between the overshoot and the final postsaccadic eye orientation (Fig. 4*A*).

We tested the relationship between these metrics for all within-blink saccades exhibiting a dynamic overshoot of at least 2° across all participants, which amounted to 204 saccades in total. For only two of these 204, the saccade overshoot preceded the time of maximum retraction and in these two cases only by a few milliseconds (Fig. 4*B*). In all other cases, the saccade overshoot occurred after maximum retraction and followed a half-normal distribution with 50% of the overshoots occurring within 42 ms after retraction maximum. Next, we analyzed the temporal relationship between the time of retraction return and the time of saccade return, which we found to be very tightly correlated along the identity line (Fig. 4*C*). Subtracting the time of retraction return from the time of saccade return resulted in a normal distribution with a mean of 3 ms (SD = 34 ms), showing that the two measures follow an almost identical time course [two-sided paired *t* test, $t(203) = -1.10$, $P = 0.27$].

Based on these results, the sequence of events involving dynamic overshoots of within-blink saccades may be described as follows (Fig. 4*D*): starting from initial eyeball orientation and position (I), the eyeball is being retracted into its socket with blink onset. This is then followed by the initiation of the saccadic eye movement within a few dozen milliseconds (II). The retraction reaches its maximum after around 100 ms, while the saccade is still in-flight (III). Global eyeball translation produces a change in orbital mechanics of the oculomotor plant such that the lever arm of the horizontal rectus muscles is changed. The neural innervation of the rectus muscles for a regularly programmed saccade could then result in overextended orientation while the eyeball is still retracted (IV). The return motion of retraction and

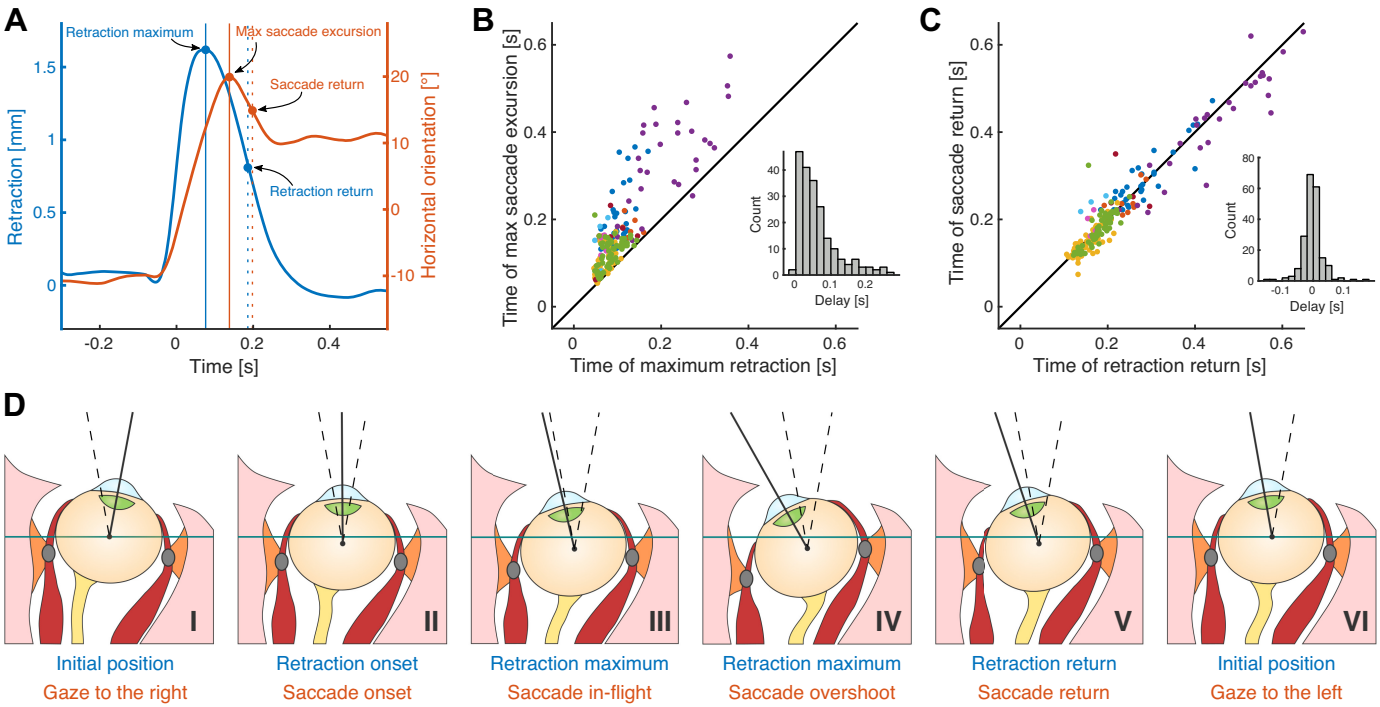

Figure 4. Relationship between dynamic overshoots and eyeball retraction. *A*: illustration of saccade and retraction metrics. The kinematics of eyeball retraction are defined by the time of maximum retraction, and the return, the time by which the retraction is at half-maximum. Analogously, saccade overshoot kinematics are defined by the maximum saccade excursion, the saccade overshoot peak, and the saccade return, which is the time by which eye orientation is half-way between peak overshoot and final position. *B*: time of maximum saccade excursion as a function of time of maximum retraction for all participants ($n = 204$). Saccade overshoot peaks occur always after retraction maximum and their delay follows a characteristic half-normal distribution. *C*: time of saccade return as a function of retraction return. The two measures are very tightly coupled to the point that a two-sided paired *t* test shows no statistical difference. Colors in *B* and *C* are identical to Fig. 3*B*. *D*: illustration of full eyeball kinematics during within-blink saccades. Initially, the gaze is directed to the right target (I). With blink onset, the eyeball retracts and the saccade is initiated afterward (II). See Supplemental Table S2 for a breakdown of the delay from saccade to blink onset for each participant. While the eyeball reaches maximum retraction, the saccade is still in-flight (III), but reaches the overshoot peak soon after (IV). Return of the retraction and return of the saccade then follow the same time course (V), before the eyeball has returned to initial position and the gaze is directed at the left target (VI).

saccade then follow an identical time course (V), before the eyeball has returned to the initial eyeball and final gaze position (VI).

Factors Contributing to Dynamic Overshoot Size

Apart from the tight temporal coupling described earlier, we were interested to see to what extent eyeball retraction could also explain the size of dynamic overshoots. One factor should be the retraction amplitude, particularly if eyeball retraction leads to changes in orbital mechanics. To test whether this is the case we performed a median split analysis of the data in Fig. 5*A*. We grouped the saccade overshoot data in two groups having a retraction amplitude below or above the median of 1.19 mm. Indeed, the group with lower retraction amplitudes had a smaller overshoot size (1.65°, SD = 1.08°) than the group with higher retraction amplitudes [3.35°, SD = 3.11°, two-sample *t* test, $t(496) = 8.16$, $P < 0.001$]. To investigate this further, we performed a linear regression analysis for each individual participant and across participants (Table 1). There is a clear correlation across participants and in the individual data of five participants. *P8* and *P9* showed very little overshoot and no correlation with maximum retraction, whereas *P6* was the only participant exhibiting (small) overshoots but no correlation with maximum retraction. Overall, this implies that large posterior retractions are necessary for large dynamic overshoots to happen. However, large retraction amplitudes do not always lead to overshoots (Fig. 5*A*). This suggests that the occurrence of dynamic overshoots critically depends on the particular saccade kinematics and the relative timing to eyeball retraction. Even though the originally programmed saccade kinematics are not accessible from our data, it is still insightful to compare the timing of saccade overshoot relative to retraction return (Fig. 5*B*). Saccades that reached their overshoot before retraction return had an average overshoot size of 2.97° (SD = 2.68°), which was larger than that of saccades that reached their overshoot after retraction return [1.09°, SD = 0.61°, two-sample *t* test, $t(496) = 7.74$, $P < 0.001$]. This suggests that the dynamic overshoots of within-blink saccades were larger if they occurred near to the maximum retraction. Correlations between individual participants and the group are given in Table 2.

Dynamic Eyeball Retraction of Saccades without Blinks

We finally also analyzed saccades without blinks. Even without blinks, the eyeball performs a small transient retraction associated with horizontal saccades (24). We wanted to test whether this retraction is directly related to the increased force exerted on the eye during the pulse phase of the saccade. If true, then the retraction should build up only

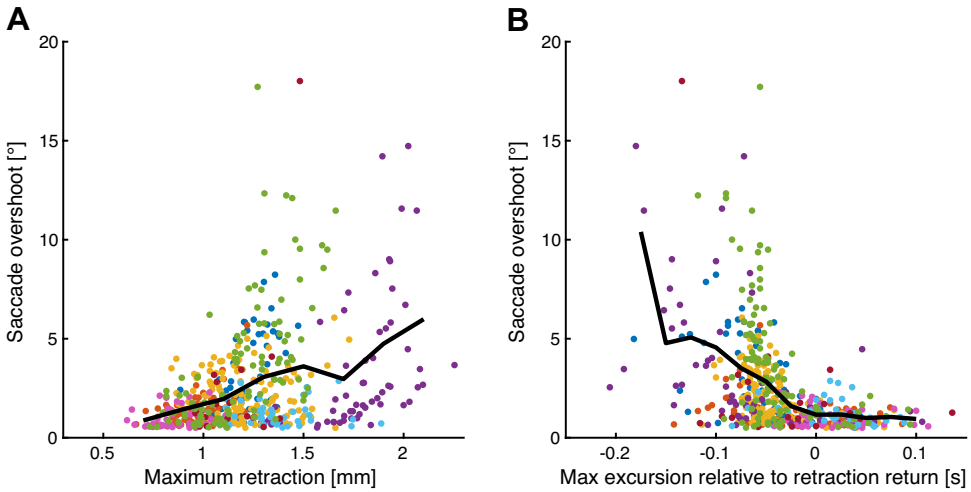

Figure 5. Factors contributing to dynamic overshoot size. *A*: saccade overshoot size as a function of maximum retraction for all within-blink saccades with an overshoot of at least 0.5° from all participants ($n = 498$). The black line is the moving average for bins of 0.2 mm width and showcases the positive correlation between retraction amplitude and saccade overshoot. See Table 1 for individual and pooled regression results. *B*: saccade overshoot size as a function of maximum saccade excursion timing relative to retraction return. Overshoots that occurred several dozen milliseconds before retraction return and hence while the eye was fully retracted, were much larger than those occurring near or after retraction return. The black line is the moving average for bins of 25 ms width. Colors in *A* and *B* are identical to Fig. 3*B*.

while the saccade is in motion and the amount of retraction should scale with saccade amplitude. We investigated this in the saccades of 5°, 10°, and 20° amplitude that were performed without blinks. Note that this data was also used for the frame-by-frame analysis of eye orientation precision in Fig. 1. Although in that analysis we used all data samples directly, here we align data to saccade onset and calculate average saccade trajectories for each participant. This averaging and alignment are bound to smear out the trajectories somewhat because of the low sampling rate of MREyeTrack compared with other eye-tracking methods. However, the comparison between orientation and retraction should still be valid as the sampling rate affects both measures in the same way.

There are two principle sources of eyeball retraction present in our data. The first is a static retraction related to eye orientation (25). The second is the dynamic retraction associated with the saccadic eye movement which we are interested in. It transiently decays after a few hundred milliseconds. To isolate the dynamic retraction, we averaged retraction trajectories across directions for all saccades of each target distance to remove the static translation. The resulting retraction trajectories clearly show the dynamic retraction associated with the saccadic eye movement (Fig. 6). Simultaneously with the saccade onset, the retraction begins to build up and reaches its maximum just before the saccade offset. After that, it slowly decays back to its initial position. The pulse phase of the saccade coincides precisely with the time window during which retraction is building up and therefore suggests that the dynamic retraction is indeed caused by the increased force exerted by the rectus muscles. This is further corroborated by the fact that the amount of retraction scales with saccade amplitude. These dynamic retractions also occur during within-blink saccades, but we did not attempt to differentiate between blink- and saccade-related eyeball retractions because the blink-related retraction is a magnitude larger.

DISCUSSION

We have shown that large transient overshoots can occur when saccades are performed together with blinks and that these overshoots can be associated with the eyeball retraction that accompanies every blink. The timing of the saccade return motion after the overshoot was very tightly coupled to the return motion of the retraction, suggesting that the overshoot is not part of saccade programming in the brainstem, but instead an incidental consequence of eyeball translation. This is corroborated by our finding that the

Table 1. *Correlation between overshoot size and maximum retraction*

Participant	Slope, °/mm	Intercept, mm	Correlation	Number
P2	8.558	−7.465	0.500***	58
P5	3.115	−1.633	0.450**	60
P6	−0.136	2.337	0.020	120
P7	7.523	−9.904	0.475**	60
P8	0.771	0.370	0.179	41
P9	−0.251	1.619	0.071	36
P10	14.602	−14.151	0.573*	18
P11	8.996	−6.906	0.610***	105
Pooled	3.162	−1.371	0.386***	498

Results of individual and pooled linear regression analysis of within-blink saccades with an overshoot of at least 0.5°. Listed are slope, intercept, Pearson's correlation coefficient, and number of within-blink saccades. ***$P < 0.0001$; **$P < 0.001$; *$P < 0.05$.

Table 2. *Correlation between overshoot size and the relative timing between maximum saccade excursion and retraction return*

Participant	Slope, °/mm	Intercept, mm	Correlation	Number
P2	−24.665	1.659	0.584***	58
P5	−5.403	1.277	0.369**	60
P6	−16.978	1.417	0.441***	120
P7	−21.539	2.066	0.472**	60
P8	−0.756	1.047	0.081	41
P9	−3.488	1.340	0.250	36
P10	−25.019	1.764	0.405	18
P11	−41.677	2.081	0.493***	105
Pooled	−20.252	1.828	0.459***	498

Results of individual and pooled linear regression analysis of within-blink saccades with an overshoot of at least 0.5°. Listed are slope, intercept, Pearson's correlation coefficient, and number of within-blink saccades. ***$P < 0.0001$; **$P < 0.001$.

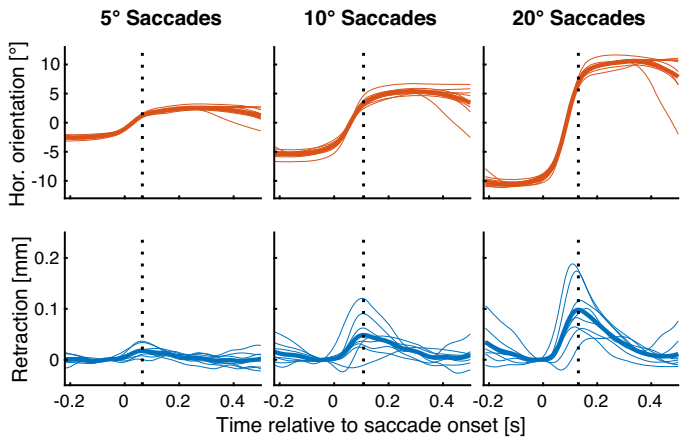

Figure 6. Dynamic eyeball retraction of saccades without blinks. Averaged eye orientation and retraction trajectories over all saccades without blinks for each of the eight participants (thin solid lines). Thick solid lines show the average across data from all participants. The retraction reaches its maximum amplitude (dotted vertical lines) once the acceleration phase of the saccade ends, after which it slowly returns to its initial position. The amount of retraction scales with saccade amplitude and hence the force exerted by the horizontal rectus muscles on the eyeball.

maximum amount of retraction explained much of the variety in overshoot size. Retraction alone, however, does not automatically cause the saccade to overshoot. Rather, retraction changes the properties of the oculomotor plant by affecting the pulleys and levers of the eye muscles such that a normal saccade command produces a different kinematic outcome. For vision, this is not a problem since the eyes are closed during the time of the overshoot. When the lid opens again the overshoot has already ceased. Saccade overshoots are likely the result of a combination of eyeball retraction and a well-timed saccade command, such that the pulse phase of the saccade coincides with the retraction being near maximum. For saccades without blinks, we also observed that the pulse phase led to small amounts of eyeball retraction that scaled with saccade amplitude. This demonstrates how closely rotational and translational motion components are connected in the execution of eye movements by the oculomotor plant.

How exactly could eyeball retraction change the properties of the oculomotor plant to generate dynamic overshoots? The torque needed to rotate the eyeball depends on the distance and angle at which the force exerted by the rectus muscles is applied, and therefore critically on the relative location of muscle pulleys to muscle insertion. At first glance, an eyeball retraction by 1 or 2 mm may not sound like it would change all that much, but horizontal rectus pulleys are located only around 8 mm posterior, and the muscle insertion is 8 mm anterior to the eyeball center (2). Therefore, eyeball retraction of 2 mm could lead to considerable change in the torque lever arm and hence the exerted force on the eyeball, even though the neural saccade command may not carry any overshoot signal. A similar scenario is encountered in the implementation of Listing's law, where the biomechanics of rotational eye movements are adjusted by gaze-dependent pulley locations. Because of this mechanical setup eye movements that are planned as two-dimensional (2-D) rotations in the superior colliculus (26) and the ocular motoneurons (27) can encompass the proper 3-D torsional rotation implied by Listing's law. Klier et al. (28) demonstrated this directly by microstimulation of the abducens nerve, while the eye was initially in varying vertical positions. Our data suggest that biomechanics are also responsible for saccade overshoot within blinks.

For the overshoot that we observed with horizontal saccades, the rectus muscles are the most involved eye muscles. However, it is conceivable that overshoots might also result from changes in the pulleys of the other muscles during retraction. It is known that eye movements during blinks depend on the initial orientation of the eye, thus implying that several muscles are involved (29, 30). Although this may affect also vertical eye movements, which we did not measure in the present study, it could also be that different involvement of muscle groups, perhaps in conjunction with small differences in the head placement in the scanner, might have contributed to the variability of the overshoot between participants in our study.

Inhibition of omnipause neurons in the brainstem could potentially lead to dynamic overshoots (1, 31), but is an unlikely explanation for the massive overshoots observed during within-blink saccades. Omnipause neurons are supposed to gate the saccadic system by firing at a tonic rate, so they need to be inhibited from triggering a saccade and resume firing once the saccade ends. Prolonged inhibition of omnipause neurons during blinks and a subsequently prolonged duration of the saccade pulse phase would produce overshoots. However, the saccades in our experiment reached their overshoot in the middle of the blink and returned to the target while the blink was still ongoing. Omnipause neurons are inhibited for the entire duration of the blink (15), so they cannot explain the occurrence of dynamic overshoots. This is further corroborated by empirical studies showing that lesioning the nucleus raphe interpositus, which contains the omnipause neurons, resulted in slower saccades but without any overshoots (32, 33).

Besides retraction, blinks also produce an upward lift of the eyeball (18) as well as rotations along the vertical axis (34). The present study focused on retraction and orientation in the plane along which the saccade is directed, i.e., horizontal but it is possible that the horizontal overshoot is additionally related to the vertical components of the blink-related eye movements. We may speculate that some of the interindividual differences we observed may also be related to interindividual differences in vertical components of the blink-related eye movement.

Our study provides a first step toward combining eye tracking with anatomical data of the oculomotor plant. The spatiotemporal resolution of our MRI data in combination with the MREyeTrack algorithm proved to be sufficient to resolve the trajectory of saccades between 5° and 20° amplitude and provided precise eyeball retraction data at the same time. However, the precision is not as good as that of conventional video-based eye-tracking methods. Specifically, the sampling rate of MREyeTrack is comparatively low and, for small saccades, likely catches only one or two samples during the saccade. Thus, it is likely that our results underestimate the amount of excursion that occurs. For very detailed studies outside of blinks, for

example for more detailed investigations into Listing's law, a hybrid approach of obtaining both video-based eye tracking and MRI data might be fruitful. This would combine high-precision data of the rotational eye motion trajectory with anatomical data of eyeball position or muscle pathway. For example, one could study muscle pathway deflections in the coronal plane with high-speed MRI while tracking rotational eye movements with a conventional eye tracker. This might be of particular interest for studying the mechanical implementation of Listing's law or eye movement disorder cases like strabismus. Although currently, the direct assessment of pulley location is not possible with the data obtained in our study, more information on muscle path deflection due to eyeball lifting and retraction during blinks would further advance the understanding of dynamic overshoots in particular and of the oculomotor plant mechanics in general. A complete understanding of eye movements, from neural implementation in the cortex and brainstem all the way to the periphery of the oculomotor plant, is essential to understanding oculomotor control in health and disease.

DATA AVAILABILITY

All data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL DATA

Supplemental Fig. S1, Supplemental Tables S1 and S2, and Supplemental Movies S1–S3: https://doi.org/10.6084/m9.figshare.c.6163152.v3.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

J.K., T.W., J.B., and M.L. conceived and designed research; J.K. and J.B. performed experiments; J.K. analyzed data; J.K., T.W., and M.L. interpreted results of experiments; J.K. prepared figures; J.K. drafted manuscript; J.K., T.W., J.B., and M.L. edited and revised manuscript; J.K., T.W., J.B., and M.L. approved final version of manuscript.

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