Conjugacy of Eyelid Movements in Vertical Eye Saccades

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recordings and found that the positioning of the coils was critical.

Vertical eye saccades are conjugate.\textsuperscript{11,12} Saccadic size differences average approximately 0.1\(^\circ\) (SD = 0.3\(^\circ\)).\textsuperscript{12} Spontaneous blinks are also conjugate.\textsuperscript{13} To our knowledge, however, the conjugacy of lid saccades has not been investigated in detail. Becker and Fuchs\textsuperscript{1} reported similarities in the main sequences for the saccades of the two eyelids in 2 of their 3 subjects. The main sequence relates to the relatively fixed relationship between amplitude, duration, and peak velocity.\textsuperscript{14} Based on these findings, Evinger et al\textsuperscript{15} assumed a good conjugacy and restricted their recordings of eyelid movements to one upper eyelid. Sibony et al,\textsuperscript{16} also implicitly assuming conjugacy in normal subjects, compared lid saccades between affected and unaffected eyelids in patients with unilateral, isolated facial paralysis. The affected eyelid consistently made smaller saccades than the fellow eyelid. Guitton et al\textsuperscript{17} recorded only one upper eyelid to provide normative data on main sequence relationships. We would argue, however, that similarities in main sequences for the two eyelids provide little detailed information on their conjugacy. Insight into this conjugacy may increase our understanding in the control of eyelid movements. We have studied this conjugacy by comparing the metrics of associated lid saccades between the two eyelids. Lid saccades were less conjugate than eye saccades.

**MATERIALS AND METHODS**

Three experiments were conducted. In the first experiment, the eyelid recording technique was validated. In the second experiment, we examined the effect of coil position on upper eyelid recordings. The conjugacy of vertical lid saccades was assessed in our third experiment.

The investigations adhered to the tenets of the Declaration of Helsinki and were approved by the institutional human experimentation committee. Informed consent was obtained from each subject after the nature of the procedures had been explained fully.

**Recording Technique and Calibration**

Eye and lid saccades were recorded by the magnetic search coil technique.\textsuperscript{1,17,18} Lid saccades were recorded with handmade round search coils. Every such coil consisted of 50 turns of insulated copper wire (diameter, 0.05 mm). A typical coil had an outer diameter of approximately 4 mm, weighed 15 mg, and was less than 0.5 mm thick. To reduce spurious induction, the leads of the coil were twisted together tightly. The coils were fixed on the lower part of the eyelid right above the pupil with a round piece of adhesive tape (diameter, 6.5 mm). Once the coils were attached, the subjects hardly noticed them. An impression of the lid coil on the lower part of the eyelid was noticed in all subjects after the experiment ended. This was not observed in the skin fold. Eye movements were recorded with commercially available search coils (Sklar Medical B.V., Delft, The Netherlands).

The field frequency was 20 kHz. All recordings were amplified to a ±10 V range, low-pass filtered at 120 Hz (–3 dB), digitized with 12-bit precision, and sampled at a frequency of 250 Hz. The recordings were stored on disk for off-line analysis. Signal noise level was less than 1.8 min arc. The recording equipment and search coils were calibrated before each recording session. Any misalignment of the coils was adjusted later, i.e., off line, by software. The accuracy of the calibration procedure was better than 0.5%.

**Experimental Procedures**

**Experiment 1: Validation of Eyelid Recording Technique.** This validation experiment addressed the principles of the recording technique. Search coils only record rotations, not translations. The voltage induced in them is proportional to the angle of rotation, relative to the direction of the magnetic field. Therefore, if eyelid movements were perfect rotations, the position of the eyelid, as projected onto a frontal plane, would relate linearly to the recorded potential from an eyelid-fixed coil in case of a vertical magnetic field.

Eight subjects, three men and five women, between 26 and 32 years of age, participated in this experiment. During the experiment, the subjects were seated facing a stimulus screen containing red light emitting diodes (LEDs), at a viewing distance of 40 cm. Head movements were restricted by a chin rest and forehead support. A ruler mounted in a frontal plane next to the upper eyelid concerned served as a calibration measure. The positions of the nine LEDs, along the mid-sagittal meridian, ranged between 35\(^\circ\) above and 55\(^\circ\) below the straight-ahead position. Subjects fixed the lit LEDs, one at a time, for 4 seconds, during which time eyelid positions (i.e., coils output voltage) were recorded. At the same time, close-up photographs of the involved upper eyelid were taken in each position. These photographs were later projected with a 10-fold magnification. Eyelid position, relative to the ruler-scale, was then measured with a reproducibility of 0.1 mm.

**Experiment 2: Effect of Coil Position.** Five subjects, three men and two women, between 24 and 36 years of age, participated in this second experiment. None of them had any history of upper eyelid disease.

Three coils were mounted on the lower part of the left upper eyelid of all subjects. One coil was fixed right above the center of the pupil, and the other two were fixed on either side. At any time, all signals of the
three lid coils were recorded simultaneously. Subjects faced a different stimulus screen than the one used in experiment 1. The LEDs were positioned along a mid-sagittal meridian, 10°, 20°, 30°, or 40° apart, symmetrically around the straight-ahead position. Head movements were restricted by a chin rest and forehead support. The viewing distance to the LED in the straight-ahead position was 1 m. Subjects were asked to alternate their gaze, on the mark of an electronically generated tone, at a frequency of 1 Hz between two lit LEDs. The four target amplitudes were presented in a randomized order. Each trial lasted 16 seconds. Before each trial, subjects could practice briefly.

Experiment 3: Conjugacy of Eyelid Movements. Ten subjects, four men and six women, between 20 and 46 years of age, served as subjects in our third experiment. Visual acuities were 20/20 or better for each eye in all subjects. None of them had any history of upper eyelid, ocular, or oculomotor disease. To ascertain that binocular vision was present, stereopsis was assessed in these subjects, by means of the Titmus stereo test (inclusion criterion: 1 min arc or better). The experimental procedures were similar to those in experiment 2, but this time only one coil was attached to the lower part of each upper eyelid, right above the center of the pupil with straight-ahead gaze. To record the associated eye saccades, search coils were mounted on both eyes. Viewing was binocular at all times.

Data Analysis
A computer program analyzed all recordings. Identical criteria were adopted for the detection of eye and lid saccades. Saccadic onset was detected if the acceleration exceeded 1000°/second² and the velocity exceeded 25°/second. Saccadic offset was detected by a deceleration of less than 1000°/second² and a velocity of less than 50°/second. Furthermore, lid saccades were included only if they occurred in conjunction with an eye saccade. For each detected eye and lid saccade, peak velocity, amplitude, and duration were determined. These data were analyzed further with a statistical software package, SPSS-X. Only primary eye saccades and the associated lid saccades were selected for analysis by an eye amplitude criterion (set at 75% of the target amplitude). Multivariate analysis of variance was used to test any observed differences between the fellow eyelids or fellow eyes. Subjects were taken as a random factor in the analyses. All interactions between fixed factors were checked on statistical significance and retained in the model if significant. To meet the requirements of normal distributions and homogeneous variances for this test, the amplitudes, durations, and peak velocities of eye and lid saccades were transformed into their logarithmic values. To describe the magnitude of the effects, means and standard deviations of the nontransformed variables are given.

RESULTS

Validation of Eyelid Recording Technique
In all subjects, a linear relationship existed between eyelid position and recorded voltage in the centrally positioned lid coil. The correlation coefficient (Pearson's r) was larger than 0.96 in every subject. Therefore, eyelid movements can be considered to be virtually perfect rotations, which justifies the use of lid coils for their registration.
Conjugacy of Eyelid Saccades

FIGURE 2. Simultaneous recordings of left and right eye saccades (left) and their associated lid saccades (subject AS; right). Vergence traces have been added. Vergence is defined as the position of the left eye (lid) minus the position of the right eye (lid). Note the variability in magnitude of 10° lid saccades. (solid line) Left eye (lid). (dotted line) Right eye (lid).

Effect of Coil Position

Coil position affected the recordings of the lid saccades ($P < 0.05$). Figure 1 (subject GW) shows the simultaneous recordings made with three adjacent lid coils on one eyelid, for typical eye saccades of approximately 20°. Their difference signals have been included. In subject GW (Fig. 1), lid saccades as recorded by the central coil were larger than those recorded with the coils either on the nasal or the temporal side. Amplitude differences between the central and the nasal lid coil averaged approximately 4.5° (SD = 0.3°; range, 4.1° to 5.3°) for these 20° saccades. Smaller differences were found between the central and the temporal lid coil; approximately 1.2° (SD = 0.4°; range, 0.1° to 1.6°) for the same target amplitude.

The displacement recorded by the central coil was not the largest in each case; the distribution of magnitudes showed idiosyncratic differences among subjects and could vary even with saccadic amplitude within a single subject.

For all five subjects together, the recorded amplitude difference between the central and the nasal lid coil averaged approximately 0.8° (SD = 0.5°) and 2.1° (SD = 1.2°), respectively.

Linearity of the central coil, though not explicitly tested as in experiment one, was nevertheless thought to be present in this experiment; the central coil matched the recordings made with one coil on the lid within one individual.

These results demonstrated that the position of the lid coils is critical for reliably recording the conjugacy of lid saccades. We therefore positioned the lid coils as symmetrically as possible, right above the pupils with straight-ahead gaze, in the following experiment.

Conjugacy of Eyelid Movements

Saccadic Amplitudes. Lid saccades were not as conjugate as their associated eye saccades ($P < 0.05$). Figure 2 shows the eye and eyelid recordings of a typical subject (Sub AS). Vergence traces have been added (vergence is defined as: the position of the left eye (lid) minus the position of the right eye (lid)). The nonconjugacy (defined as: amplitude differences between the two eyelids or between the two eyes) averaged approximately 0.5° (SD = 0.3°; range: 0° to 1.2°)
upward eyelid saccades

right eyelid (deg)

left eyelid (deg)

downward eyelid saccades

left eyelid (deg)

right eyelid (deg)

upward eye saccades

right eye (deg)

left eye (deg)

downward eye saccades

right eye (deg)

left eye (deg)

FIGURE 3. Scatterplot of saccadic size of individual eye (lid) saccades of the right eye (lid) versus saccadic size (degrees) of the left eye (lid) at the four target amplitudes in our group (n = 10). Saccades of the lids and eyes are separated and have been pooled for each direction, either upward or downward. Correlation coefficients (Pearson’s r) were 0.97 for the lid saccades and 0.99 for the associated eye saccades.

for his 10° lid saccades and increased with the target amplitude to 2.0° (SD = 0.9°; range: -0.5° to 5.3°) for his 30° lid saccades. By contrast, his associated eye saccades (Fig. 2) were very conjugate: the nonconjugacy averaged approximately 0.2° (SD = 0.1°; range: 0° to 0.4°) for both 10° and 30° saccades.

In the group as a whole, the nonconjugacies of lid saccades increased with the target amplitude (P < 0.05) and were approximately 8% of the target amplitude. Those nonconjugacies averaged, in ascending order for our four target amplitudes, approximately 0.7° (SD = 0.5°), 1.7° (SD = 1.5°), 2.1° (SD = 1.6°), and 3.4° (SD = 2.6°), respectively. Nonconjugacy of the lid saccades was similar for the two directions, upward and downward (P > 0.05). By contrast, the nonconjugacies of the associated eye saccades were only approximately 1% of the target amplitude (P > 0.05) and were similar for the two directions, upward and downward (P > 0.05). Figure 3 shows this nonconjugacy in separated scatterplots of lid and eye saccades for each direction, either upward or downward. The scatter is much larger for lid saccades than for eye saccades.

In subject AS (Fig. 2), lid saccades of the right eyelid were larger than those of the left eyelid for 10° lid saccades. By contrast, at 30° saccades, the left eyelid made larger saccades than the right eyelid, except in one upward saccade. The associated eye saccades were always larger on the right side. Similar variations in nonconjugate lid saccades both within one target amplitude and between target amplitudes were observed in seven other subjects. In two subjects, it was always the same eyelid (the left) that made the larger saccades.

Another observation in all subjects was that the eyelids often showed transient overshoots at all four target amplitudes. Figure 4 shows a typical example of such a transient overshoot. Recordings of the associated horizontal eye movements have been included. The transient overshoots were observed mostly in downward saccades. The returning phase was either fast, as in blinks, or slow, as in glissades. Such transient overshoots occurred more frequently at larger target amplitudes. There was no consistent relationship between the target amplitude and the magnitude of the transient overshoot or its appearance. The transient overshoots of the eyelids were sometimes similar to those of the eyes commonly observed in downward saccades. However, they occurred considerably more frequently in the lids than in the eyes. In addition, transient overshoots of lid and eye saccades occurred independently of one another.

To discriminate between transient overshoots of the eyelids and voluntary blinks, we analyzed the hori-
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LID SACCADES

HORIZONTAL EYE SIGNALS

FIGURE 4. Typical example of a transient overshoot of lid saccades (upper panel). Recordings of the associated horizontal eye signals are included (lower panel).

Figure 4. Typical example of a transient overshoot of lid saccades (upper panel). Recordings of the associated horizontal eye signals are included (lower panel).

Lid Eye Coordination. Durations of lid saccades were similar to those of the associated eye saccades only at the 10° target amplitude (paired sample t-test; \( P > 0.05 \)). At the other target amplitudes, on average, lid saccades had longer durations (paired sample t-test; \( P < 0.05 \)) than their associated eye saccades in the two directions; these differences were in the downward direction approximately 6.6 msec (SD = 23.9 msec) for 20° saccades, 8.0 msec (SD = 21.6 msec) for 30° saccades, and 9.5 msec (SD = 21.7 msec) for 40° saccades. In the upward direction, the durations differed more: on average, approximately 15.3 msec (SD = 30.8 msec), 18.1 msec (SD = 37 msec), and 10.1 msec (SD = 23.1 msec), respectively.

Lid saccades had their saccadic onset, on average, approximately 6 msec (SD = 4.1 msec; range, 0 msec to 20 msec) later than their associated eye saccades (paired sample t-test; \( P < 0.05 \)) in downward and upward directions at all target amplitudes.

Saccadic Peak Velocities. Saccadic peak velocities for the associated eye saccades (\( P < 0.05 \)). Downward eye saccades were, on average, approximately 0.3° (SD = 1.0°) for 10° saccades and 1.4° (SD = 2.1°) for 40° saccades larger than upward eye saccades.

In all subjects, the position of the eyelid showed more intersaccadic instabilities (Fig. 2) than that of the eye, irrespective of saccadic direction at all target amplitudes. This confirms earlier reports by Becker and Fuchs.

Saccadic Duration. The duration of lid saccades was the same (\( P > 0.05 \)) for the two eyelids, irrespective of saccadic direction at all target amplitudes. In our group, the duration was approximately 104 msec (SD = 43.8 msec) for 10° saccades and increased with the target amplitude to 193.5 msec (SD = 48.2 msec) for 40° saccades. Saccades of the left and right eye also had similar durations (\( P > 0.05 \)) that increased with the target amplitude from approximately 92 msec (SD = 13 msec) for 10° saccades up to 183.8 msec (SD = 38.7 msec) for 40° saccades. The equality of duration in the two eyes was irrespective of saccadic direction and present at all target amplitudes. In addition, the duration of upward and downward lid saccades was similar for the two directions (\( P > 0.05 \)), at similar target amplitudes, as was the duration of the associated eye saccades.

Saccadic onset of the two eyelids was almost simultaneous: within 1.9 msec (SD = 2.2 msec; range, 0.0 msec to 8.0 msec) for 10° saccades and within 3.0 msec (SD = 5.0 msec; range, 0.0 msec to 16.0 msec) for 40° saccades, irrespective of saccadic direction. Saccadic onset occurred just as often first in the left eyelid as in the right eyelid (paired sample t-test; \( P > 0.05 \)). For comparison, eye saccades had their saccadic onset within approximately 0.6 msec (SD = 2.0 msec; range, 0.0 msec to 8.0 msec) of one another.

Saccadic Peak Velocities. Saccadic peak velocities...
were, on average, higher in the left eyelid than in the fellow eyelid \((P < 0.05)\), irrespective of saccadic direction at all target amplitudes. However, the eyelid, left or right, in which the higher peak velocity occurred varied inconsistently within and between trials in one subject.

In the group as a whole, the differences in peak velocities increased with the target amplitude and averaged, for downward lid saccades, approximately 20.6°/second \((SD = 23.8°/second)\) for 10° saccades, 45.6°/second \((SD = 55.8°/second)\) for 20° saccades, 50.3°/second \((SD = 45.5°/second)\) for 30° saccades, and 65.8°/second \((SD = 66.3°/second)\) for 40° saccades. Upward lid saccades differed less in their peak velocities: on average, approximately 12.87 second \((SD = 42.57 second)\), respectively. By contrast, for the associated eye saccades, which were, on average, higher in the left eyelid than in the fellow eyelid \((P < 0.05)\), irrespective of saccadic direction at all target amplitudes. However, the eyelid, left or right, in which the higher peak velocity occurred varied inconsistently within and between trials in one subject.

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By examining the amplitudes, the peak velocities, and duration of individual saccades of the two eyelids, we found that, compared to its counterpart, the larger eye sagittal axis, comparable to a visor, each point of the upper eyelid would, in principle, rotate equally. Our findings therefore imply that the various parts of the upper eyelid have different rotational axes. We propose several possible causes for this multitude of axes. The tarsal plate, largely consisting of dense fibrous tissue, is flexible and gives shape to the upper eyelid. During lid movements, it may closely follow the shape of the underlying structures, notably the sclera and the cornea. Because the cornea has a smaller radius than the sclera, the part of the eyelid overlying the cornea also might be more curved than the part overlying the sclera. As a result, those parts of the eyelid sliding over the nasal and temporal parts of the cornea will diverge more \((i.e., \text{relative to each other})\) than if the same parts slid over the sclera. What is more, the movements of the various parts of the upper eyelid relative to each other will depend on the gaze position. As a result, the effect of the cornea will probably be smaller with lid saccades than with blinks because the eye and the lid move comparably in lid saccades, whereas in blinks, the lid totally covers the converging eye. There may be another reason for the different recordings we found for the various parts of the upper eyelid. The nasal and temporal parts of the upper eyelid are qualitatively differently attached. Briefly, the nasal attachment is firm, whereas the temporal one is fairly loose. As a result, the axes of rotation of the temporal part of the upper eyelid may have a wider range in space than those of the more nasal parts of the eyelid. In studies such as ours into the conjugacy of upper eyelid movements, all these variations within a single eyelid may best be avoided by mounting lid coils as symmetrically as possible, \(e.g.,\) right above the center of the pupil in primary gaze position.

Moreover, we found that the recordings of lid saccades were affected by the positioning of the coils. If the upper eyelid rotated around a single rotational axis, comparable to a visor, each point of the upper eyelid would, in principle, rotate equally. Our findings therefore imply that the various parts of the upper eyelid have different rotational axes. We propose several possible causes for this multitude of axes. The tarsal plate, largely consisting of dense fibrous tissue, is flexible and gives shape to the upper eyelid. During lid movements, it may closely follow the shape of the underlying structures, notably the sclera and the cornea. Because the cornea has a smaller radius than the sclera, the part of the eyelid overlying the cornea also might be more curved than the part overlying the sclera. As a result, those parts of the eyelid sliding over the nasal and temporal parts of the cornea will diverge more \((i.e., \text{relative to each other})\) than if the same parts slid over the sclera. What is more, the movements of the various parts of the upper eyelid relative to each other will depend on the gaze position. As a result, the effect of the cornea will probably be smaller with lid saccades than with blinks because the eye and the lid move comparably in lid saccades, whereas in blinks, the lid totally covers the converging eye. There may be another reason for the different recordings we found for the various parts of the upper eyelid. The nasal and temporal parts of the upper eyelid are qualitatively differently attached. Briefly, the nasal attachment is firm, whereas the temporal one is fairly loose. As a result, the axes of rotation of the temporal part of the upper eyelid may have a wider range in space than those of the more nasal parts of the eyelid. In studies such as ours into the conjugacy of upper eyelid movements, all these variations within a single eyelid may best be avoided by mounting lid coils as symmetrically as possible, \(e.g.,\) right above the center of the pupil in primary gaze position.

The conjugacy of normal lid saccades, the main topic of this article, has not been studied previously in great detail. Several clinical studies suggest that Hering’s law of equal innervation may apply to lid movements. Becker and Fuchs’ compared the main sequences of the two eyelids and found that they were similar. From these data, they inferred good conjugacy. Main sequences, however, are curves that are
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We found that vertical lid saccades indeed were considerably less conjugate than the associated eye saccades. These inconsistencies indicate that main sequences do not reflect accurately the metrics of individual lid saccades and are of little value when the conjugacy of movements is assessed.

A good conjugacy of lid saccades is to be expected because their premotor saccadic control is shared with that of eye saccades, which are conjugate. In both movements, the same motor nucleus is involved. Discharge patterns of levator and superior rectus motoneurons are similar, though levator motoneurons discharge at lower firing rates than do superior rectus motoneurons. Our data agree with a shared control of both eye and lid saccades: We found that lid saccades always had their onset shortly after that of the eyes. The interval between the two varied little. For both kinds, upward saccades were smaller than downward saccades. In addition, saccades of the two eyelids had similar durations and had their onset almost simultaneously. However, the amplitudes and peak velocities of lid saccades varied considerably between the two sides. This variation reflects a control of lid saccades far less refined than of eye saccades. Obviously, there is no functional need for a control of lid saccadic conjugacy as tight as of eye saccadic conjugacy. The good conjugacy of eye saccades serves to foveate binocularly a newly selected visual target and thus prevents diplopia. Several stimuli that disrupt the functional yoking of eye saccades have been shown to cause adaptive changes that restore this functional yoking. These adaptive changes are known as nonconjugate adaptations. In case of lid saccades, the movements do not have to be conjugate as long as the lids do not prevent each eye from seeing. We do not know whether nonconjugate adaptation of the eyelids may also occur. Carefully examining patients with unilateral ptosis may provide us with an answer. Our data will then serve as normal values.

We found that transient, downward overshoots frequently occurred. Surprisingly, they have been reported only by Evinger et al. Our first impression of these overshoots was that they were blinks made during downward saccades. However, because they were not associated with converging eye movements, typical of blinks, we think they are separate entities. Evinger et al. found weak bursts of electromyographic activity in the orbicularis oculi muscle during large saccades, but not during small saccades. This confirms similar reports. We found that the transient overshoots occurred in saccades of any magnitude, and we therefore question the role of the orbicularis oculi muscle in the genesis of transient overshoots.

We also found that there were bigger velocity differences between the two eyelids in downward than in upward lid saccades. Because downward lid saccades result from the relaxation of the levator and passive downward forces whereas upward ones result from its activation, this is not surprising.

The principal finding of our experiments was that lid saccades are not as well yoked as eye saccades. Obviously, there is no functional need for such a good conjugacy in lid saccades. To what extent this poor yoking of lid saccades may be affected by disease, aging, and imposed adaptive stimuli remains to be seen.

Key Words

conjugacy, eyelid movements, lid saccades, saccades, search coil

Acknowledgments

The authors thank A. C. Slingerland for his technical contributions in all phases of the data collection process and for providing a computer program for data analysis.

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