Scleral Search Coils Influence Saccade Dynamics

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Frens, M. A. and J. N. van der Geest. Scleral search coils influence saccade dynamics. J Neurophysiol 88: 692–698, 2002; 10.1152/jn.00457.2001. The scleral search coil technique is commonly used for recording eye movements. The goal of this paper is to investigate to what extent the placement of scleral search coils onto the eyes influences the kinematics of saccades. To that end saccadic eye movements of human subjects were recorded with an infrared video system, while they wore coils and we compared the main sequence properties with recordings in which no coils were mounted on the eyes. It was found that saccades last longer (by about 8%) and become slower (by about 5%) when both eyes wear coils. This is truly due to the fact that the coils are on the eyes and not due to other factors that are part of this method, such as the scleral anesthesia. The influence of coils in both eyes was also observed when one coil was mounted on one eye only. Therefore the effect that the coils have on the eye movements cannot be attributed to purely mechanical factors, such as inertial load on the eyeball or increased friction. Rather the coils appear to change the oculomotor command signals that drive the saccadic eye movements.

INTRODUCTION

The scleral search coil method, introduced by Robinson (1963) and refined by Collewijn et al. (1975), is widely used to measure the position of the eye. Eye position is determined by placing a silicon annulus on the eye. This annulus contains a coil of thin copper wire. When the subject is placed in an AC magnetic field, the position of the eye can be determined from the amplitude of the induction current in the coil. The method has a high spatial (≪1°) and temporal (≪1 ms) resolution and is therefore considered to be the gold standard in eye-movement recording (Collewijn 1998).

The major disadvantage of the method is that it is invasive. Therefore the experimental time is limited to about 30 min, since most subjects cannot tolerate a coil in their eye for a longer period, even when the eye is anesthetized. Additionally, one risks corneal edema and abrasion if coils are worn too long. Furthermore, by introducing an object in the eye, one changes the inertia (by about 5%) and the friction and therefore the force that the eye muscles have to generate to perform a movement. Robinson (1964) showed that a huge increase of the inertia of the eye (by almost a factor 100) resulted in relatively small changes in the shape of a saccade. However, the kinematic properties of the saccades were not investigated.

Not only purely mechanical factors may influence the kinematics of the saccades. For instance, the discomfort of wearing scleral search coils may change the oculomotor command signals. These signals are known to depend heavily on various factors, such as the alertness of the subject (van Opstal and van Gisbergen 1987) and the nature of the stimuli (e.g., Frens and van Opstal 1995).

To evaluate whether recording eye movements invasively with scleral coils influences the characteristics of the movement, saccadic eye movements from human subjects were recorded with an infrared video system (EyeLink, SensoMotoric Instruments, Berlin, Germany) immediately before (pre-series) and during (test series) the period they had scleral search coils in their eyes. Using the video system the dynamic properties of the eye movements were determined and we compared the preseries saccades with the test series saccades.

METHODS

Eye movement recording

Eye movement recordings were made using the EyeLink system. During the recordings the head was immobilized with the use of a bite-board. Binocular two-dimensional (2D) eye position (monocular eye position in subject D, see following text) was sampled at a frequency of 250 Hz. The EyeLink technique is based on optical detection of the pupil. The coils were large enough to leave the pupil completely uncovered. It is therefore unlikely that the coils could directly affect the EyeLink recordings (see also Van der Geest and Frens 2002).

Search coils and anesthesia

Two-dimensional search coils obtained from Skalar (Delft, The Netherlands) were used. These coils have a weight of about 85 mg. The coils were inserted according to the instructions provided by the manufacturer, with the leads exiting the eyes toward the nose. Before insertion the eyes were anesthetized with a few drops oxybuprocain (0.4%) in HCl (pH 4.0). The present experiments were focused on eye movement data obtained by the video method, and as such the coils generally were not used for recording eye position. However, in a few cases eye position was measured with the coils as well as with the EyeLink system to test the reliability of the latter system.

Figure 1 summarizes these results. Detailed results of this direct comparison between the coil measurements and the video recordings have been published elsewhere (Van der Geest and Frens 2002). The top panel shows two simultaneously recorded traces. The bottom panels show the parameters (amplitude, peak velocity, and duration, respectively) that were obtained by the two methods for each saccade. Note that there is no systematic difference between the two methods apart from a slightly higher measure of peak velocity and duration by the video system. These differences are constant over the whole parameter range, since the slope in each bottom panel is not significant.

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different from 1 \((P > 0.3)\). Not surprisingly, there was also a good correlation between the main sequence parameters that were obtained from the coil and the video recordings. In the remainder of this paper only video recordings under the different conditions will be compared. Therefore any systematic changes in the saccade properties are truly due to the experimental procedures.

**Experimental procedure**

The subjects were asked to make series of self-paced saccadic eye movements between two black spots on a light-gray background. The spots (diameter: 0.5°) were displayed on a 21-inch monitor at a distance of 50 cm from the subject. In each trial the spots were placed symmetrically around the straight-ahead direction and were visible throughout a trial. The position of the spots varied from trial to trial. Five distances between the spots (approximately 1, 2, 4, 15, and 30°) and four orientations of the axis through the spots (0, 45, 90, and 135°, where 0° is to the horizontal right) were used, resulting in 20 conditions. Each condition lasted for 20 s, allowing for roughly 20 target-directed saccades to be made. The total recording time was about 10–20 min.

Each experiment started with a baseline measurement (preseries). Subsequently, one of the following procedures was performed.

1) Both eyes were anesthetized, and a coil was inserted on each eye.
2) Both eyes were anesthetized, without inserting a coil.
3) Only the left eye was anesthetized, and a coil was inserted in this eye.

A second recording was made (test series) with identical stimulus conditions as in the preseries. The time between anesthesia and the onset of the second recording was about 4 min. After the experiments the coils were removed according to the instructions provided by the manufacturer.

**Subjects**

Subjects were seven male volunteers that were recruited from our department and included both authors. Three subjects participated in all experimental procedures. Three subjects (E, F, and G) only participated in procedure 1. Subject D only participated in procedure 3. All subjects had no known oculomotor or uncorrected visual abnormalities, except subject D, who is monocular and has a prosthesis in his right orbit. Four subjects were highly experienced in wearing scleral search coils. The other three subjects had never worn eye coils before.

**Calibration**

The video system was calibrated using the built-in nine-dot routine. In short, the subject had to fixate nine consecutive dots that appeared in random order at 3 × 3 evenly spaced locations on the monitor (14° horizontally and 10° vertically). The manufacturer’s software produced the subsequent output of the eye position in pixels of the stimulus monitor. These pixel values were converted to horizontal and vertical eye orientation angles, taking the distance between the eye and the monitor into account. Calibration was performed before the preseries and before the test series, because the cameras had to be removed to place the coils.

**Data analysis**

From the data files the amplitude, duration, and peak velocity of all saccades were determined, including both the targeted saccades and small correction movements. Saccadic onset and offset sample points for each saccade were determined using a velocity criterion of 30°/s. The onset sample point was defined as the sample point closest to 4 ms before this level was crossed. The offset sample point was taken to be closest to 4 ms after eye velocity had dropped below this criterion.

Horizontal and vertical amplitude were calculated as the difference in horizontal and vertical eye position at the time of saccadic onset and saccadic offset. Horizontal and vertical amplitudes were transformed to polar coordinates, yielding the direction and (radial) amplitude of the saccade. Duration was calculated as the difference in time of the offset and onset of the saccade, and the maximum radial velocity reached during the saccade was taken as the peak velocity. Radial eye velocity was calculated from the differentiated horizontal and vertical position signals.

The relation between saccade amplitude and peak velocity and the relation between saccade amplitude and duration (the so-called “main sequence” relations) (Bahill et al. 1975) was determined. Through the peak-velocity:amplitude relation an inverse-exponential function was fitted, using the Nelder–Mead simplex method (Nelder and Mead 1965)

\[
V_{\text{peak}} = S(1 - e^{-\text{Amp}^\beta})
\]
where $V_{\text{peak}}$ is the peak velocity (°/s), $Amp$ is the saccade amplitude (°), and $S$ and $\lambda$ are the fitted parameters [the saturation level (°/s) and the length constant (°/s), respectively].

The duration:amplitude relation was fitted by a straight line

$$\text{Dur} = \text{Offset} + \text{Gain} \times \text{Amp}$$

where $\text{Dur}$ is the duration of a saccade (ms), $\text{Offset}$ is the intercept with the y-axis (ms), and $\text{Gain}$ (ms/°) is the slope of the line. These lines were determined by linear regression.

RESULTS

Recordings with two coils

Placing two 2D coils in the eyes of a subject did have a clear and significant influence on the velocity profiles of the saccades. This is illustrated in Fig. 2. Video recordings of position and velocity profiles are shown for saccades with amplitudes of about 30° to the right, made by one subject without and with coils inserted.

As was stated in METHODS, several kinematic parameters from the saccadic eye movements, as well as their mutual relationships, were determined. These relationships varied with the direction of the saccades, which is in line with the literature (Smit et al. 1990). Figures 3 and 4 show the peak velocity:amplitude (Fig. 3) and the duration:amplitude (Fig. 4) relations for one subject for the eight directions in which saccades were made. Note that in many of the directions clear differences can be observed between the situation with coils (open circles) and without (closed squares). Although some directions seem to be more affected than others, a systematic relationship across subjects between the direction of the saccade and the magnitude of the kinematic changes was not observed.

For each eye and each saccade direction the four fitted parameters (see METHODS) was determined, before and after

![FIG. 2. Radial position (A) and radial velocity (B) profiles of horizontal saccades with amplitudes of approximately 30° to the right. In the “without coil” condition, mean amplitude was 29.0 ± 0.7°, mean peak velocity was 526 ± 34°/s, and mean duration was 96 ± 7 ms; in the “with coil” condition, mean amplitude was 29.3 ± 0.3°, mean peak velocity was 459 ± 53°/s, and mean duration was 125 ± 16 ms for this subject (subject A, right eye, procedure 1).](https://www.jn.org/)

![FIG. 3. Saccade peak-velocity versus amplitude relationships for 8 saccade directions for the condition with coils (circles, thin line) and without coils (squares, thick line) with their fits according to Eq. 1 (subject A, right eye, procedure 1).](https://www.jn.org/)
insertion of the coils. Figure 5 shows all four fit parameters for each direction for the same subject as in Figs. 3 and 4. The systematic effect of coil placement is visible in the saturation velocity and duration gain plots, while there was no difference between the two eyes. For each parameter the difference between the preseries and the test series (for each eye, direction and subject, n = 112) was calculated by simply subtracting the values. If the coils have no effect on the saccade dynamics, the distributions of these differences should not be significantly different from 0. This was not the case, however. The two parameters that could be determined most reliably (as tested by means of a Monte Carlo bootstrap procedure) (Efron and Tibshirani 1993) were significantly affected (P < 0.01, t-test). These were an (on average) 8% decrease in the saturation level of the peak-velocity:amplitude relation and an (on average 5%) increase of the gain of the duration:amplitude relation. No differences were seen between experienced and inexperienced subjects nor was a change in the effect over the time that the subjects wore the coils found (differences between the first 10 min and the second 10 min of the test series; for the saturation level −1.37 ± 24.0 (SE) ms/°, for the duration gain 0.02 ± 0.19, P > 0.6). Thus, in general, saccades became slower with an increased duration. Table 1 shows the mean change for each parameter.

There was a good relation between the strength of the coil effect in the peak-velocity:amplitude and the duration:amplitude relationships. This correlation can be seen qualitatively by comparing Figs. 3 and 4. The directions, in which saccade peak velocity is affected, also show a change in duration. This correlation is shown quantitatively in Fig. 6: if the gain is increased in the amplitude/duration relation, there is a decrease in the saturation level of the peak-velocity:amplitude relation. The $R^2$ value of 0.36 is highly significant ($P < 0.001$). This finding is not trivial: the duration and the peak velocity are derived from the raw data on the basis of independent criteria, and the two parameters are fitted to different relations.

Recordings after anesthesia only

To investigate whether the observed changes were due to the fact that there were coils in the eyes or to other factors in the procedure (such as anesthesia or fatigue), the same procedure as described above was followed without actually inserting the coils in three of our subjects. No systematic changes in kinematic properties were observed, as can be observed in Table 1 and Fig. 7.

Recordings with one coil

After establishing that the changes in kinematic properties were actually due to the placement of the coils on the eyes, the cause of these changes was investigated. Therefore the experi-
ment was repeated with a coil in the left eye only. If the change was due to purely mechanical factors, such as friction or an increase of the weight of the eyeball, it was expected that the left eye should be slower and not different from what was found in the two-coil condition. Meanwhile the right eye, having no coil inserted, should not behave differently from the preseries.

However, if the oculomotor command signals are changed, it is expected that the eye movement properties of both eyes should be influenced. This can be a result of feedback of the changed mechanics, but also other factors (such as discomfort or blur of the visual image) may play a role. Figure 8 shows the results of this experiment.

As one can see, the effects of wearing a coil are still present, although slightly more variable. More importantly, no consistent differences can be seen between the left (with coil) and the right (without coil) eye. Table 1 shows that the mean change of the parameters of either eye was not significant different from the effects that were observed in the two-coil condition. Therefore it is likely that the effects observed in the two-coil condition cannot be attributed to purely mechanical factors but also are the result of an influence on the oculomotor signals.

**DISCUSSION**

The scleral search coil technique is a widespread tool for the measurement of (saccadic) eye movements. However, in this paper it is shown that, by inserting coils in the eyes, the kinematic properties of the saccadic eye movements are changed. The absolute effects are most prominent for relatively large saccades, because the main effects found were on the gain of the duration:amplitude relation and the saturation level of the peak-velocity:amplitude relation, so that deviations with the preseries are larger for larger amplitudes. These changes are due to the insertion of the coils themselves, rather than to the other factors involved in this method and occur when one coil is placed in one eye as well as when two coils are placed on both eyes. Purely mechanical factors cannot explain these results, since the effects show up in both eyes when the coil is only present in one eye. Therefore we expect that the insertion of the coils changes the neural commands that drive saccades.

Several other factors are known to influence these signals. For instance making saccades in the dark reduces the velocity of saccades considerably compared with saccades in the light (Smit et al. 1987). Also, for instance, fatigue and the use of diazepam have a similar effect (Rothenberg and Selkoe 1981; van Opstal and van Gisbergen 1987). It is our hypothesis that the discomfort that is caused by the coils, despite anesthesia, may be responsible for the observed effects. This could also explain the large intersubject variation in the one-coil experiment. The discomfort of one coil may be negligible for some, but not for others. In this

**TABLE 1. Differences between preseries and test series parameters for the three procedures**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Procedure 1 (two coils)</th>
<th>Procedure 2 (anesthesia alone)</th>
<th>Procedure 3 (one coil in left eye)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration vs. amplitude</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gain, ms/°</td>
<td>0.15 ± 0.04*</td>
<td>-0.02 ± 0.02†</td>
<td>0.14 ± 0.06</td>
</tr>
<tr>
<td>Offset, ms</td>
<td>0.11 ± 0.34</td>
<td>1.01 ± 0.37†</td>
<td>2.22 ± 1.02</td>
</tr>
<tr>
<td>Peak velocity vs. amplitude</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturation level S, °/s</td>
<td>-11.9 ± 4.4*</td>
<td>3.6 ± 5.0†</td>
<td>-12.7 ± 12.1</td>
</tr>
<tr>
<td>Length constant λ, °</td>
<td>0.25 ± 0.18</td>
<td>0.34 ± 0.25</td>
<td>0.23 ± 0.33</td>
</tr>
</tbody>
</table>

Values are means ± SE. Differences are given as the value of the test series minus the value of the preseries. Means were taken from the individual differences for each eye and each direction. * Significantly different from 0 ($P < 0.01$; tested for procedure 1). † Significantly different from procedure 1 ($P < 0.01$; tested for procedures 2 and 3).

**FIG. 6. Correlated effects in the peak-velocity:amplitude and duration:amplitude relation.**

Correlation between the coil-induced gain change of the duration:amplitude relation and the change of the saturation level of the peak-velocity:amplitude relation. Data are pooled for all subjects. Each dot represents a saccade direction of a subject. The fitted line is a 1st-order approximation of the relation. Note that the effect appears to be stronger in the upper left quadrant, where increased duration was coupled to decreased peak velocity. The dashed lines indicate the average value for the 2 parameters.
respect it is important to note that a different magnitude of change in the experienced or novice subjects was not observed. Furthermore, the additional discomfort related to the increasing time of wearing coils is not likely to be of as much influence as wearing of the coils themselves, since an additional effect over time during the experimental session was not observed.

Some subjects reported that the main discomfort seems to be due to the lead of the coil, rather than to the coils itself. We therefore tested the effect of coils for which the leads were removed in two of the experienced subjects. The effects were as big as were found in the same subjects with intact coils (the average differences across all eight directions and two eyes and two subjects between the coil-without-leads and the intact-coils experiments: for the velocity saturation levels 11.8 ± 13.0 °/s and for the duration gains 0.073 ± 0.070 ms/°, both P > 0.3).

An alternative explanation for the observed effect could be that the coils often cause slightly blurred vision, which might influence saccadic properties. However, we have tried to quantify this blur using the Snellen acuity test, but it is probably too small to be detected in such a way. Therefore we consider this a less likely explanation for the findings in these subjects. Finally, it may be that the brain tries to compensate for the changes in inertia of the eye and therefore changes the oculomotor commands. This explanation also seems improbable. The increased inertia requires a larger force in the eye muscles. Thus this hypothesis predicts systematically faster saccades in the “non-coiled” eye of the one-coil experiment. Figure 7 and Table 1 show that this is not the case.

Implications for other studies

To what extent do these results affect the outcome of previous studies that used scleral search coils for the recording of saccadic eye movements? For many studies the implications are limited. Studies that compare recordings under one condition with recordings under another condition may have incorrect absolute values for the saccadic velocity traces, but the differences between the conditions probably remain.

Possibly data that may be affected by these coil artifacts are to be found in studies regarding interactions between saccades and other eye movements, such as vergence or smooth pursuit (e.g., Collewijn et al. 1995, 1997; Erkelens et al. 1989; Minken and van Gisbergen 1996; van Leeuwen et al. 1998; Zee et al. 1992), because it is unclear how coils affect movements with much lower velocities. The subtle interplay between these oculomotor subsystems may be disturbed by the use of coils, and it would be worthwhile to investigate this interplay by a noninvasive method.

Chronically implanted search coils are commonly used for recording eye movements in animal research. This method has been successfully applied in various species, such as monkeys, cats, rabbits, mice, chameleons, and goldfish. Recently, Stahl et al. (2000) showed that coils substantially influence the amplitude of the slow phase gain of compensatory eye movements in mice, 3 days after they had been surgically implanted. However, in this study it is more likely that mechanical constraints of the coils are responsible for the observed effects, since the inertia of the coil is relatively much greater compared with the inertia of the mouse eye. Furthermore, these coils are chronically implanted and the surgery also may affect the properties of the orbit. It is unknown whether these coils induce changes in the other “not operated” eye. Due to its small size the mouse is probably the most likely animal to be influenced by the insertion of coils. However, it may be worthwhile to investigate to what extent chronically implanted coils influence eye movements in other species.
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