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TMS-induced blinking assessed with high-speed video: optical disruption of visual perception

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Abstract

It is known that TMS can induce blinking, but it is unknown to what extent and at what time TMS-induced blinking can cover the pupil. We applied single-pulse TMS with a leftward and rightward monophasic current through a round coil over the occipital pole in 8 healthy subjects, using high-speed video to monitor left or right eye with a spatial resolution of 0.1 mm and a temporal resolution of 2 ms. We plotted eyelid position relative to upper and lower pupil borders as a function of time after TMS for each subject and current direction. We found 2 blinks in every subject, an isolated late blink with one current direction and a superimposed early and late blink with the other current direction, in accordance with our previously reported association between a leftward and rightward lower coil rim current and an early blink in right and left eye, respectively. Blink extent varied, but 4 subjects showed total pupil covering with both current directions. Blink timing varied, but pupil covering was initiated as early as 32 ms after TMS and pupil uncovering was completed as late as 200 ms after TMS. We found no saccades. We conclude that TMS can cause an important optical disruption of visual perception.

Keywords

Blinking; Video recording; Kinematics; Pupil; Transcranial magnetic stimulation (TMS)

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Introduction

Blinking is a brief eye closure. It protects, moistens, and cleans the corneal surface. During the closing phase of a blink, the upper eyelid shows a large downward and a small nasalward movement and the lower eyelid shows a small nasalward and a negligible vertical movement (Kennard and Glaser 1964; Doane 1980a, b; Evinger et al. 1984; Arrigg and Miller 1985; Collewijn et al. 1985; Shore 1985; Macdonald & Maurice 1991; VanderWerf et al. 2003; Frueh et al. 2005; Casse et al. 2007; Zhu and Chauhan 2007). The upper eyelid position during a blink is determined by passive elements, the orbicularis oculi (facial nerve), the levator palpebrae superioris (oculomotor nerve), and the superior tarsal muscle (sympathetic system). In addition to spontaneous, voluntary, and reflex blinks, blinks can be elicited by direct stimulation of the upper and lower motor neuron innervating the orbicularis oculi muscle. The upper eyelid is a strong (Volkmann et al. 1980; Riggs et al. 1981) and red-pass (Moseley et al. 1988; Robinson et al. 1991; Ando and Kripke 1996) filter, obscuring almost all vision when the eye is closed.

Transcranial magnetic stimulation (TMS) can non- invasively change neural activity (Barker et al. 1985) and has been used for more than two decades to study vision (Cowey 2005; Hallett 2007). Single-pulse TMS over the occipital pole can disrupt vision not only during 2 periods after the offset of a brief visual stimulus (Amassian et al. 1989; Corthout et al. 1999a) but also during 2 periods before the onset of a brief visual stimulus (Corthout et al. 1999a; Corthout et al. 2000). The 2 later effects were interpreted as direct effects on neural activity in the underlying visual cortex (Corthout et al. 1999a), reflecting initial and recurrent processing, respectively (Corthout et al. 1999b). However, not all disruptive occipital TMS effects on vision are direct effects on the underlying neural activity (Corthout et al. 2007), and the 2 earlier effects could well be due to TMS-induced blinking. Still, pupil covering by TMS-induced blinking has never been characterized or even demonstrated.

The existence and latency of occipital TMS-induced blinking have been reported in 2 prior studies with infrared recording (Beckers and Homberg 1991; Corthout et al. 2000), which can detect eyelid movement with high sensitivity and measure eyelid movement onset with high precision. However, the effects of TMS have never been assessed with high-speed video recording, which has several advantages. First and foremost, eyelid movement relative to the pupil borders and, therefore, pupil covering cannot be assessed with infrared recording. Second, occipital TMS has so far been reported to induce only “small” blinks, even with a large round coil and 100% stimulator output (Beckers and Homberg 1991), but eyelid movement amplitude can only be relatively indirectly estimated with infrared recording. Third, occipital TMS has so far been reported not to induce saccades (Beckers and Homberg 1991), but eyelid and eyeball movement can only be relatively indirectly differentiated with infrared recording. Additionally, infrared recording studies yielded conflicting reports on occipital TMS-induced eyelid movement composition and onset, despite using similarly strong stimulation parameters. Indeed, Beckers and Homberg (1991) reported only isolated late blinks, with latencies not shorter than 35-40 ms, whereas Corthout et al. (2000) found both isolated late blinks and superimposed early and late blinks, with latencies as short as 9 ms for the early blink and as short as 24 ms for the late blink.

Studying the ocular effects of occipital TMS with high-speed video recording can thus reveal extent and timing of pupil covering by blinks, improve the assessment of the amplitude of blinks and the existence of saccades, and help resolve the issue of the number of components and the latency of blinks.

The current paper focuses on the effects of occipital TMS-induced blinking on vision, reporting data that reveal eyelid position relative to upper and lower pupil borders as a function of time after TMS. A future paper will focus on the causes of occipital TMS-induced blinking, reporting data that are consistent with the lateralized early blink arising via direct stimulation of the intracranial facial nerve (similar to the one arising with the TMS coil over the extracranial facial nerve) and with the bilaterally symmetrical late blink arising via auditory and somatosensory reflex blinking (similar to the one arising with the TMS coil in the air and under the arm).

Methods

Subjects were 8 healthy students, 18-25 years. Experiments were conducted with their written informed consent and with the approval of the Departmental Ethics Committee. Subjects were rewarded GBP 20 per session.

Magnetic stimuli were generated with a Magstim 200 and a 90-mm ring sandwich coil. Stimulation intensity was set to 90 or 100% of the maximum output. Subjects wore tight latex bathing caps to mark the coil position, had their heads stabilized by a chin and forehead rest, and looked straight ahead. The coil was held over the occiput, in a near-coronal plane with its center 0-2 cm from the mid- sagittal plane, and with its upper rim about 2 cm from the head and its lower rim against the head, 1-2 cm rostral to the inion. The current direction indicating arrows on the lower coil rim, indicating the direction of its initial current, were directed to the left or right by a 180° rotation about the longitudinal axis of the coil handle, thereby changing the coil side that was against the head. The current direction (CD) allowed inducing 1 isolated blink or 2 superimposed blinks in a given eye and was accordingly labeled CD1 or CD2.

The effect of the current direction is explained by two prior studies. Corthout et al. (2000) demonstrated that TMS can induce eyelid movement as part of an early blink. In one of the experiments, we delivered magnetic stimuli with a Magstim 200 and a 90-mm ring sandwich coil located over the occipital pole and assessed TMS-induced eyelid movement simultaneously in both eyes with infrared recording. We found that TMS could induce eyelid movement not only as part of an isolated late blink but also as part of a superimposed early and late blink. Corthout et al. (2001) demonstrated a lateralizing CD effect on the early blink. In one of the experiments, we delivered magnetic stimuli with a Magstim 200 or a Magstim Super Rapid and a 90-mm ring sandwich coil located over the occipital pole with both current directions and assessed the occurrence of TMS-induced early blinks simultaneously in both eyes with video recording. For each stimulator (but in an opposite way), we found that one current direction affected one eye more than the other eye while the reverse was true for the other current direction and that one eye was more affected by one current direction than by the other current direction while the reverse was true for the other

eye. The latter means that an eye can show an isolated late blink with one current direction and a superimposed early and late blink with the other current direction. Henceforth, we refer to the early and late component of the superimposed early and late blink as ‘the early blink’ and ‘the superimposed late blink’, respectively.

In this study, we assessed TMS-induced eyelid movement relative to the pupil with video recording, using a Kodak Ektapro EM 20. In pilot experiments, TMS-induced blinking was monitored simultaneously in both eyes, showing for example how one applied current direction can differently affect movement of the two upper eyelids. In a first stage, the eyelid showing a superimposed early and late blink started its descent, while the eyelid showing an isolated late blink remained stationary. In a second stage, the eyelid showing a superimposed early and late blink decelerated its descent, stopped its descent, or reversed its motion into an ascent, while the other eyelid showing an isolated late blink still remained stationary. In a third stage, the eyelid showing a superimposed early and late blink accelerated its descent again, restarted its descent again, or reversed its motion back into a renewed descent, at the same time that the eyelid showing an isolated late blink started its descent for the first time. The descending motions were then coordinated in both eyes; the eyelids moved in unison, the only difference being that the eyelid showing a superimposed early and late blink kept a lower position relative to the eyelid showing an isolated late blink.

In the main experiment, TMS-induced blinking was monitored in left or right eye, precisely showing eyelid position relative to upper and lower pupil borders. Spatial resolution was as high as 0.1 mm because of monitoring one zoomed-in eye at a time, which allows for a spatial resolution 3 times higher than that with monitoring both eyes simultaneously. Temporal resolution was as high as 2 ms because of a recording speed of 500 Hz. The upper eyelid position was measured during a 200-ms period after the TMS pulse; every frame (2 ms) during the fast descending motion and every fifth frame (10 ms) during the subsequent slow ascending motion. The time of the TMS pulse was identifiable because TMS induced an artifact in a video frame (which was thus marked as the video frame at time t = 0). The timing of this TMS- induced artifact was confirmed with the timing of recorded TMS-induced LED activations.

We assessed as a function of time after TMS the position of the inner side of the lower border of the upper eyelid that was vertically above the center of the pupil (called the position of ‘the upper eyelid border’). We also determined at time t = 0, the position of the upper pupil border, the position of the lower pupil border and the position of the inner side of the upper border of the lower eyelid that was vertically below the center of the pupil (called the position of ‘the lower eyelid border’). The positions of the upper eyelid border, the upper pupil border and the lower pupil border were then expressed as a distance relative to the position of the lower eyelid border. Distances in pixels were transformed to distances in mm by recording the length in pixels of a 10-mm scale held vertically in front of the eye of each subject.

When the upper eyelid border crossed a pupil border, the vertical position of that pupil border was not always identical to one of the attained vertical positions of the upper eyelid border. In such cases, the following approach was taken. First, the time that the upper eyelid

border reached the upper pupil border was taken as the time that the upper eyelid border attained the vertical position that was just above (rather than just below) the vertical position of the upper pupil border. Second, the time that the upper eyelid border reached the lower pupil border was taken as the time that the upper eyelid border attained the vertical position that was just below (rather than just above) the vertical position of the lower pupil border. The reason for these 2 chosen options is that an upper eyelid border above the upper pupil border and below the lower pupil border implies no pupil covering and total pupil covering, respectively (whereas the 2 discarded options both imply some partial pupil covering). The 2 chosen options are thus both functionally clear and equal to an upper eyelid border exactly at the pupil borders.

Our method contained two possible inaccuracies. First, the time that the upper eyelid border reached a pupil border was always based on the position of that pupil border before TMS. Second, the time that the upper eyelid border reached the upper and lower pupil border was sometimes taken as the time that the upper eyelid border was just above the upper and just below the lower pupil border, respectively. The size of the first possible inaccuracy was deemed negligible in view of pilot experiments, and the size of the second possible inaccuracy was necessarily less than 2 ms. Nevertheless, we controlled for both possible inaccuracies in the following ways. First, we assessed directly on the video frames when the descending upper eyelid border reached the actual rather than the pre-TMS pupil borders and compared these real times with the tabulated times. Second, if one frame did not capture the upper eyelid border exactly reaching an actual pupil border, then the time that the upper eyelid border reached that actual pupil border was taken as the averaged time between the times that the upper eyelid border was just above and just below that actual pupil border.

We determined the following parameters for 2 current directions and 8 subjects. First, we plotted the position of the upper eyelid border relative to the position of the upper pupil border, the lower pupil border and the lower eyelid border as a function of time after TMS (Fig. 1). We listed the time after TMS that the descending and ascending upper eyelid border reached these 3 borders and listed the distances between the upper eyelid border and these 3 borders. Second, we plotted the descent amplitude of the upper eyelid border as a function of time after TMS (Figure not shown). We listed the descent amplitude of the upper eyelid border attained at the first six consecutive 10 ms after TMS, and the time after TMS that the upper eyelid border attained the first six consecutive millimeters of descent amplitude. Third, we plotted the descent speed of the upper eyelid border as a function of time after TMS (Figure not shown). We listed the resolvable descent amplitude, the peak descent amplitude, and the peak descent speed of the upper eyelid border, and the corresponding onset times after TMS for the CD1 blink and the CD2 blink, as well as for the isolated late blink, the early blink, and the superimposed late blink. The descent speed plots served not only to show the descent speed magnitudes but also to help delineate the early blink and the superimposed late blink.

Tables provide the values of all the measurements of variables described above for each subject as well as 4 sample statistics across the 8 subjects (mean value and its standard error; minimum value and maximum value). In text and tables, times are given as integers, positions with 1 decimal and velocities with 2 decimals. P-values for differences between

CD1 and CD2 in extent and timing of blinks were calculated with two-tailed paired-samples *t* tests using Microsoft Excel. Tables are provided in the supplementary material.

Results

Figure 1 shows as a function of time after TMS the vertical position of the upper eyelid border relative to the pre-TMS upper pupil border, lower pupil border, and lower eyelid border. It shows that all 8 subjects blinked with each current direction: an isolated late blink with CD1 and a superimposed early and late blink with CD2.

Figure 1 reveals that out of 16 cases, the upper eyelid border reached the upper pupil border in 13 cases, the lower pupil border in 9 cases, and the lower eyelid border in 4 cases. It also reveals the extent of the blinks in relation to pupil covering across the 8 subjects. It furthermore reveals that the upper eyelid border reached more borders with CD2 than CD1.

Figure 1 shows that the descending upper eyelid border reached borders sooner with CD2 than CD1 in all subjects in whom a border was reached with both current directions. It also shows that the ascending upper eyelid border reached borders later with CD2 than CD1 in all subjects bar one in whom a border was reached with both current directions. (Note that the only subject in whom the ascending upper eyelid border reached borders sooner with CD2 than CD1 was also the only subject in whom the upper eyelid border reached smaller peak descent amplitude with CD2 than CD1.)

Table 1A shows the time after TMS that the descending and ascending upper eyelid border reached the upper pupil border, the lower pupil border, and the lower eyelid border, for the CD1 blink and the CD2 blink. The descending upper eyelid border reached each pupil border significantly earlier with CD2 than CD1. These differences in time were not due to differences in initial distances, as shown in Table 1B. There was no functional difference between the tabulated descent times and the real descent times. Full details are in the supplementary material.

Table 2A shows the descent amplitude of the upper eyelid border at the first six consecutive 10 ms after TMS, for the CD1 blink and the CD2 blink. Descent amplitudes were significantly larger with CD2 than CD1 for each of the last 5 times. Table 2B shows the time after TMS that the upper eyelid border attained the first six consecutive millimeters of descent amplitude, for the CD1 blink and the CD2 blink. Descent times were significantly earlier with CD2 than CD1 for each descent amplitude. Full details are in the supplementary material.

Table 3 shows the resolvable descent amplitude, the peak descent amplitude, and the peak descent speed of the upper eyelid border as well as the corresponding onset times after TMS, for the CD1 blink and the CD2 blink. The CD2 blink started significantly earlier and descended significantly further than the CD1 blink, but these blinks attained their maximum descent at the same time. Full details are in the supplementary material.

Other relevant results can be derived from the Tables, such as duration of total pupil covering, duration of descent during pupil crossing, duration of descent before initiation of

pupil covering or duration of descent before completion of pupil covering. Full details are in the supplementary material.

We never observed TMS-induced saccades.

Discussion

We applied single-pulse occipital TMS with a left and right current direction in 8 subjects as in previous TMS disruption studies of visual perception. We assessed the upper eyelid position relative to the pupil in the left or right eye using high-speed video with a spatial resolution of 0.1 mm and a temporal resolution of 2 ms. We found a TMS-induced blink in all 8 subjects, with each eye showing an isolated late blink with one current direction and a superimposed early and late blink with the other current direction.

This study demonstrated that occipital TMS-induced blinking can cover the pupil and characterized the extent and the timing of such pupil covering. The extent of the blinks varied, but the entire pupil was covered in more than half of the 16 cases (2 current directions and 8 subjects), and the entire sclera was covered in a quarter of the 16 cases. The timing of the blinks varied, but pupil covering could be initiated and completed as early as 32 and 44 ms, respectively, and pupil uncovering could be initiated and completed as late as 140 and 200 ms, respectively. Our data thus show that pupil covering can be spatially and temporally important.

Although the present study is the first to measure eyelid movement relative to the pupil for TMS-induced blinks, a previous study measured eyelid movement relative to the pupil for a voluntary blink (Volkmann et al. 1980). However, their experiment was not designed to reveal the timing with which the descending upper eyelid border reached the upper and lower pupil border. Indeed, they recorded video frames at only 80 Hz, and a temporal resolution of 12.5 ms is of the same order of magnitude as the entire descending transit time across the pupil. Moreover, they measured descent onset time only indirectly and apparently conservatively, stating: “Blink onset (time 0) is the time at which the trigger detected the blink. The sensitivity was set to detect the blink before the upper lid began to cover the pupil.” Also, they showed data for only 1 subject.

Although the present study provides the first video recording data on the extent and timing of blinking induced by TMS, 5 previous studies used other techniques to characterize blinking induced by TMS over the posterior scalp. Three papers provided eyelid response onset times in healthy subjects to occipital or parieto-occipital TMS with electromyography of the orbicularis oculi (Cocito and De Mattei 1992; Ghezzi et al. 1992; Maccabee et al. 1988). Comparison with our data shows that electromyography recording measures onset time 5-10 ms earlier than video recording. Full details are in the supplementary material. Two papers provided eyelid motion onset times to occipital TMS with infrared recording (Beckers and Homberg 1991; Corthout et al. 2000). Comparison with our data shows that infrared recording measures onset time at about the same time as video recording. Full details are in the supplementary material.

The present results show that blinks induced by occipital TMS with a large round coil and high stimulator output are not all late monophasic blinks with small amplitude and latency greater than 35-40 ms, as reported in the first infrared recording study of occipital TMS-induced blinking (Beckers and Homberg 1991). Our data indicate that they may have underestimated the late TMS-induced blink. Indeed, the isolated late blink in our 8 cases had a peak descent amplitude as large as 10.5 mm, a resolvable descent onset as early as 26 ms, and a descent amplitude as large as 1.3 mm by 40 ms. Moreover, our data indicate that they may have underestimated TMS-induced blinking to an even greater extent by missing the early TMS-induced blink. Indeed, the superimposed early and late blink in our 8 cases had a peak descent amplitude as large as 10.3 mm, a resolvable descent onset as early as 12 ms, and a descent amplitude as large as 2.7 mm by 40 ms.

This study provides no evidence for the existence of single-pulse occipital TMS-induced saccades, which might interfere with visual perception of brief visual stimuli. It has already been reported that occipital TMS does not result in saccades (Beckers and Homberg 1991; Meyer et al. 1991), but their reports were based on infrared recording, and high-speed video recording is a more reliable method to detect saccades. Several arguments support the absence of TMS- induced saccades. First, not only were saccades absent in these 8 subjects, they were also absent during similar high-speed video experiments in other subjects. Second, we recorded with a temporal resolution of 2 ms and a spatial resolution of 0.1 mm, ensuring high sensitivity. Third, we stimulated with a monophasic stimulator at 90-100% output and a 90-mm ring sandwich coil, ensuring highly effective TMS. Fourth, TMS-induced blinks are unlikely to have prevented the detection of TMS-induced saccades. Indeed, the upper eyelid border did not reach the lower pupil border (leaving a visible pupil) in 7 cases and did not reach the lower eyelid border (leaving a visible globe) in a further 5 cases. Moreover, in the remaining 4 cases where the upper eyelid border did reach the lower eyelid border, the globe became invisible as late as 70 ms after TMS in 1 case, remained invisible as short as 12 ms in 1 case, and returned visible as early as 80 ms after TMS in 1 case.

Single-pulse TMS over the occipital pole can not only induce both early and late blinking motions (Corthout et al. 2000) but can also yield both short-delay and long-delay dips in visual discrimination performance before visual stimulus onset (Corthout et al. 2003), with the short-delay dip occurring about 10 ms before a brief visual stimulus and the long-delay dip occurring about 50 ms before a brief visual stimulus. It is appealing to associate the late blink with the long-delay dip (“dip0”) and the early blink with the short-delay dip (“dipX”). However, the present study indicates that such an association is erroneous, as both blinks can be implicated in a dip0 effect and as probably neither blink can be implicated in a dipX effect.

This study showed that the late blink itself can disrupt vision by pupil covering and that the early blink can increase pupil covering during the late blink, but not that the early blink itself can cover the pupil. Although it cannot be ruled out under particular experimental circumstances, the early blink itself is not likely to disrupt vision by pupil covering, as suggested by our findings and by studies that found no effect of local facial nerve stimulation on vision (Beckers and Zeki 1995; Amassian et al. 1998).

This study provided further evidence that dip0 is almost certainly caused by pupil covering and that dipX is almost certainly not caused by pupil covering. The dip0 effect was initially ascribed to pupil covering as it occurred at times assumed compatible with blinking and as it occurred similarly strongly over all tested parieto-occipital scalp positions (Corthout et al. 1999a). Stronger evidence now follows from the finding that TMS-induced blinks can cover the pupil and that the timing of such pupil covering correlates with the timing of dip0. Under conditions that allowed for an isolated dip0, the dip0 effect was found to have started to disrupt vision as fast as 30 ms and as slow as 50 ms before visual stimulus offset and to have started to disrupt vision completely as fast as 60 ms and as slow as 70 ms before visual stimulus offset (Corthout et al. 2000; Corthout et al. 2003). These 30- to 50-ms and 60- to 70-ms intervals tally nicely with the 32- to 62-ms and 44- to 76-ms intervals reported here for the time after TMS that the descending upper eyelid border arrived at the upper and lower pupil border, respectively. The dipX effect was initially defined as the effect that occurred too late to be caused via pupil covering and too early to be caused via direct disruption of visual stimulus processing (Corthout et al. 2000) and was isolated subsequently (Corthout et al. 2003). In addition to arguments beyond the scope of this paper, the dipX effect is difficult to reconcile with pupil covering because of its timing. Indeed, we found that a dipX effect at 19.4 ms before pixel illumination offset decreased visual stimulus discrimination from 100 to 60% (Corthout et al. 2003), while upper eyelid descent at 20 ms after TMS has now been found to be only 0.3-0.7 mm. Also, we found a dipX effect at 9.4 ms before pixel illumination offset (Corthout et al. 2000), so that the entire visual stimulus had impinged on the retina before TMS has now been found to cause any upper eyelid descent, starting only 12 ms after TMS. Furthermore, we found a dipX effect that was sometimes absent at 20/30 ms and always maximal at 10/20 ms before pixel illumination (Corthout et al. 2003), contrary to what has now been found for the early blink, with a descent starting 12-14 ms after TMS and with a peak descent starting 24-28 ms after TMS.

Finally, but importantly, we note that in perceptual experiments involving occipital TMS, performance impairments might be produced or exacerbated by pupil covering rather than via neural events in the underlying cortex, probably even more so with repetitive-pulse TMS. Of course, extent and timing of pupil covering, and extent and timing of performance impairments, depend on experimental conditions and subjects. However, while it is difficult to use high-speed video with every TMS disruption study of vision, investigators can use these high-speed video data as a ‘safety guide’ for their own experimental conditions and subjects as our data can be expected to show cases with early descent and late ascent. Indeed, we used highly effective TMS. Moreover, we used 8 different subjects and not only the CD1 but also the CD2 current direction. For example, this study can be used as a ‘safety guide’ to infer times before which no pupil covering can be expected to be initiated. First, investigators can estimate the initial distance between upper eyelid border and upper pupil border. Second, investigators can then refer to Table 2A, showing that the maximum upper eyelid border descent attained at the first six consecutive 10 ms after TMS was 0.0, 0.7, 1.1, 2.7, 7.4 and 10.0 mm, respectively, or refer to Table 2B, showing that the minimum time after TMS that the upper eyelid border descent attained the first six consecutive millimeters was 28, 37, 41, 43, 45 and 47 ms, respectively.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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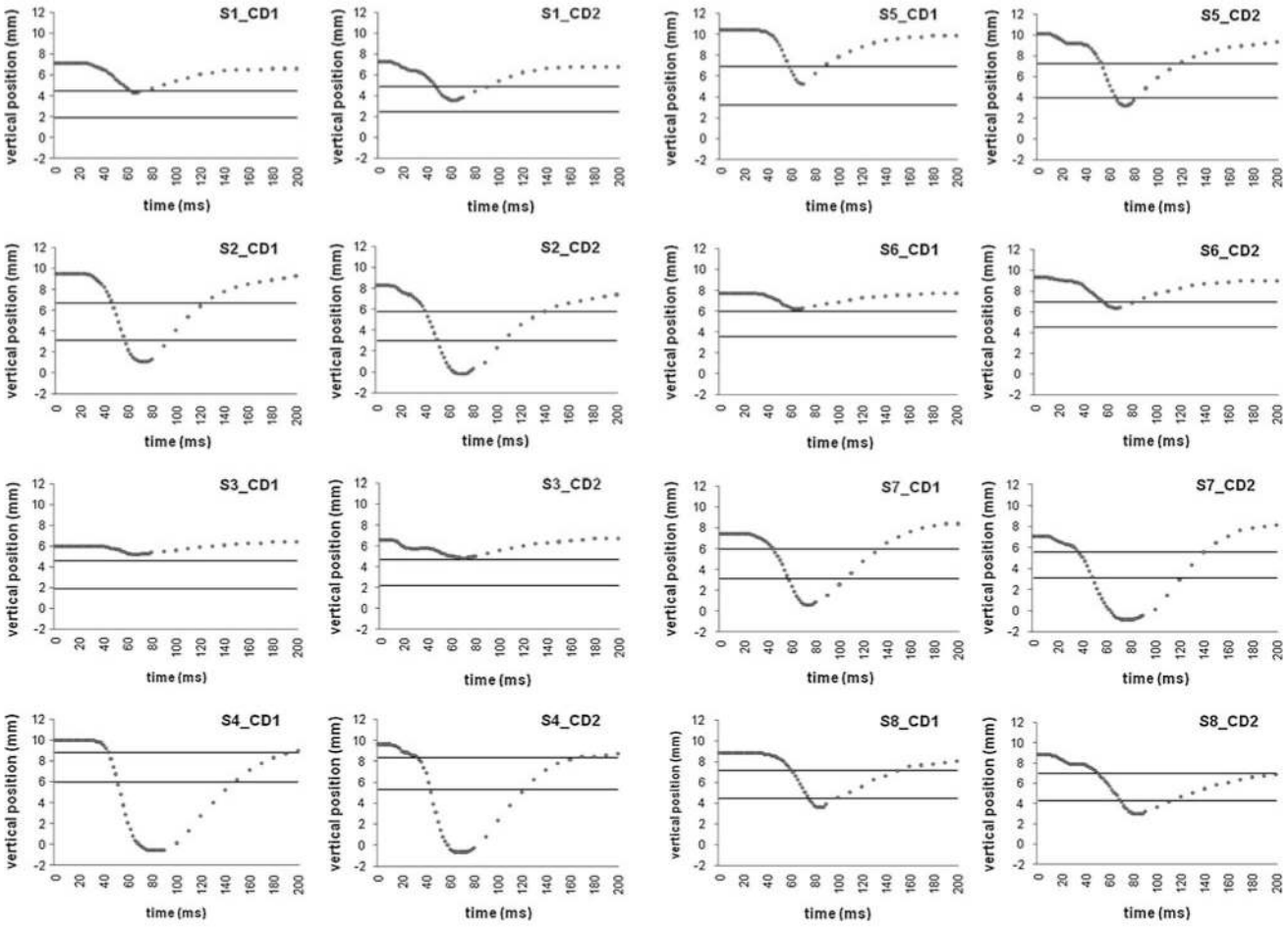

Fig. 1.

Shows as a function of time after TMS the *vertical* position of the *upper* eyelid border above the pre-TMS *lower* eyelid border for different current directions and subjects. This *vertical* position was measured as the distance between the inner side of the *lower border* of the *upper* eyelid after TMS and the inner side of the *upper border* of the *lower* eyelid before TMS on a *vertical line* through the center of the pupil. The *upper* and *lower horizontal lines* show, respectively, the position of the *upper* and *lower* pupil border before TMS. The Y = 0 coordinate corresponds to the position of the lower eyelid border before TMS. A *negative* and *positive vertical* position indicates that the *upper* eyelid border was, respectively, below and above the pre-TMS *lower* eyelid border; a *decreasing* and *increasing vertical* position indicates that the *upper* eyelid border is, respectively, descending and ascending. Data are plotted from time of TMS to 200 ms later. The position of the *upper* eyelid border was measured every 2 ms before its peak descent amplitude and every 10 ms after its peak descent amplitude. **a**, **b** Show data for the first and second four subjects, respectively