Transcranial stimulability of phosphenes
by long lightning electromagnetic pulses

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Abstract

The electromagnetic pulses of rare long (order of seconds) repetitive lightning discharges near strike point (order of 100 m) are analyzed and compared to magnetic fields applied in standard clinical transcranial magnetic stimulation (TMS) practice. It is shown that the time-varying lightning magnetic fields and locally induced potentials are in the same order of magnitude and frequency as those established in TMS experiments to study stimulated perception phenomena, like magnetophosphenes. Lightning electromagnetic pulse induced transcranial magnetic stimulation of phosphenes in the visual cortex is concluded to be a plausible interpretation of a large class of reports on luminous perceptions during thunderstorms.

APPENDIX: Erratum and Addendum

The comparison of electric fields transcranially induced by lightning discharges and by TMS brain stimulators via $\vec{E} = -\partial_t \vec{A}$ is shown to be inappropriate. Corrected results with respect to evaluation of phosphene stimulability are presented. For average lightning parameters the correct induced electric fields appear more than an order of magnitude smaller. For typical ranges of stronger than average lightning currents, electric fields above the threshold for cortical phosphene stimulation can be induced only for short distances (order of meters), or in medium distances (order of 50 m) only for pulses shorter than established axon excitation periods. Stimulation of retinal phosphene perception has much lower threshold and appears most probable for lightning electromagnetic fields.

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Introduction

Transcranial magnetic stimulation (TMS) of neural activity in the human brain has developed into an established method for neurophysical medical diagnosis and psychiatric treatment [1, 2]. In particular, stimulation of the visual cortex by pulsed magnetic fields directed at suitable positions towards the head has been reported to invoke phosphenes in probands, which are perceived as luminous shapes within the visual field [3]. Here we show that the near-field electromagnetic pulses of natural rare long (1-2 s) repetitive lightning strokes can be expected to lead to neural induction currents above threshold values in the same order of magnitude regarding frequency, duration and strength of stimulation as used in medical TMS. For a small fraction of lightning flashes a near observer (ca. 20-200 m) should experience repetitive stimulation of perception activity similar to clinical TMS effects. We conclude evidence for a plausible interpretation of a large class of reports on luminous phenomena during thunderstorms as lightning electromagnetic pulse induced transcranial magnetic stimulation of phosphenes in the human brain. An observer is likely to classify such an experience under the preconcepted collective term of ”ball lightning”.

Motivation: the phosphene interpretation of “ball lightning” reports

According to a comprehensive review by Stenhoff [4], “ball lightning” (BL) has been reported in the open air, indoors, and within aircraft. Around one third of BL events may be attributed to observations of stationary corona discharges in strong thunderstorm electric fields [4]. The majority of observations which have been analyzed in different surveys (cited ibidem) reported BL to be directly succeeding a cloud-to-ground lightning flash. Some hypothetical scenarios for BL-like dust-gas fireballs appearing in very specific environmental situations after a stroke in sand or water have been suggested as a possible explanation [5–7].

We here propose that a large class of reports (about the half) characterizing BL as luminous roundish objects arising in coincidence with lightning flashes and appearing to move slowly at eye level of an observer for a few seconds (often accompanied by whitish noises and smells) can be interpreted as magnetic phosphenes.

The phosphene interpretation of “ball lightning” has been proposed earlier by J. Swithenbank (reported in Ref. [4]) after personal BL observation, and was discussed (and first brought in context with TMS) in a skeptical review of BL theories [8]. Other authors have in Ref. [9] cursorily dismissed the phosphene hypothesis with an erroneous argument consid-
Magnetophosphenes: visual perception by induction

The normal process of visual perception comprises the conversion of optical stimuli into electric signals by photoreceptors in the retina, and subsequent propagation of sensor potentials to the visual cortex in the occipital brain by neuron networks. Transmission of stimuli occurs in form of action potentials caused by processes opening and closing selective ion channels in the cell membranes. Action potentials form irrevocably if the depolarization of a cell membrane due to external stimuli exceeds a threshold value of $U_{thr} \sim 20 \text{ mV}$ above the resting potential ($-50 \text{ mV} > U_{rest} > -70 \text{ mV}$). The intensity of a stimulus is encoded by the frequency of subsequent action potentials [11].

Magnetic phosphenes are visual perceptions caused by time varying magnetic fields $B(x, t)$, described by the vector potential $A(x, t)$ from $B = \nabla \times A$, that induce sufficiently strong electric fields $E_{ind}(x, t) = -\partial_t A(x, t)$ to cause a local potential (determined via $E_{ind}(x, t) = -\nabla U_{ind}(x, t)$) on the membrane exceeding $U_{ind} > U_{thr}$. These change the membrane potential and trigger an action potential either in the retina, in transmitting neurons, or directly in neurons of the visual cortex. The resulting visual perception is termed retinal phosphene or cortical phosphene, respectively, according to the location of the stimulus at the retina or in the cortex.

Cortical phosphenes induced by transcranial magnetic stimulation

Transcranial magnetic stimulation (TMS) is a method for noninvasive selective magnetic stimulation of local brain areas [1, 2]. Perceptible stimulation can be achieved by application of either single magnetic pulses or by repetitive pulses (rTMS) through stimulation coils placed on the outside of the head. Typical duration of a single neural TMS pulse is in the
order of 250-450 µs, and typical repetitive pulse frequencies are in the range of 1-50 Hz. The transient magnetic field induces a local electric field inside the brain which can form an action potential in the stimulated area if $U_{\text{ind}} > U_{\text{thr}}$.

Cortical phosphenes, which are perceived as luminous shapes within the visual field, are reported when the TM stimulus is applied to the area of the visual cortex and the local induced field amplitude exceeds values in the range of 20-50 V/m, with varying thresholds in different subjects [3]. Phosphenes are perceived in various shapes (ovals, bubbles, lines, patches) within the visual field, mostly appearing white, gray or in unsaturated colours [12]. The duration of perception follows the duration of the single pulses or the whole repetitive cycle respectively. Phosphenes appear moving when the stimulation coil is shifted or the fixation site is changed. Impressions appear stronger and brighter with increasing stimulus strength [13].

Retinal phosphenes have even lower threshold values than their cortical counterparts [14, 15]. Motivated by the availability of many well documented clinical TMS studies on cortical phosphenes, and by the established specifications of TMS induction coils, we restrict to those in the following comparison with lightning electromagnetic pulses (LEMPs).

**Repetitive LEMPs and TMS**

Phosphenes in clinical TMS are reported to occur only during the actual duration of stimulation (without significantly longer lasting after effects). A perception caused by LEMPs can therefore be duly expected for duration at least comparable to or longer than typical TM stimulation experiment times of 250-450 µs.

Negative (CG-) downward discharges occur in 90% of cloud-to-ground lightning. Typical CG- discharges begin with an electric stepped leader breakdown and a first return stroke, and are in most cases followed by multiple subsequent strokes, which are each initiated by a dart leader pulse through the pre-established channel. Single stroke CG- flashes have a typical duration of several hundred microseconds. Positive cloud-to-ground flashes (CG+) have rarer occurrence and are usually limited to a single stroke, but may occur with higher continuing currents for longer discharge times up to 0.1 s [16].

Stimulation by single stroke CG- or CG+ discharges may, as a consequence, cause brief phosphene perceptions (if the stimulus strength is above threshold), but is not able to explain reported BL durations in the order of seconds.
Long CG-flashes consisting of repetitive strokes occur at stroke intervals between 4-500 ms with a mean value of 50 ms \[16\], which in fact are exactly compatible to standard rTMS frequencies in the range of 1-50 Hz. Phosphene perception by clinical rTMS has been reported for 3-5 successive pulses or more. The average number (multiplicity) of lightning strokes per flash is also between \( n = 2 \) and 5, but more than 20 strokes per flash with a total duration up to two seconds have been observed in detection networks \[17\]. Further subsequent strokes (possibly up to more than 40) with decreasing amplitudes often fail to enter the statistics by not exceeding the threshold of remotely distributed detectors.

Although the electromagnetic pulses of the stepped leader and first return stroke could lead to induced fields above the phosphene threshold, these are of minor importance for the long term field evolution of high multiplicity flashes. The further discussion can be limited to the effects of following dart leaders and subsequent return strokes. Repetitive stimulation by these multiple return strokes of \( n > 20 \) can occur with durations \( t > 20 \cdot 50 \text{ ms} \) in the order of several seconds.

**Calculation of lightning electromagnetic fields**

Now we address the question if natural repetitive cloud-to-ground LEMPs generated by nearby strokes are able to transcranially induce electric fields comparable to those generated by clinical TMS (of around 20-50 V/m), and thus sufficiently strong to stimulate similar sensory perceptions.

For this purpose we have calculated the near electromagnetic fields of lightning discharges for various types and parameters of naturally occurring flashes. Previously published field calculations have mostly been restricted either to far fields (> km) relevant to lightning detection networks, or to direct impacts relevant to engineering problem of lighting protection.

The model and numerical methods of our near field LEMP calculations, including the effects of channel tortuosity and arbitrary observer location, are based on Refs. \[16, 18–20\]. For details on the method and general results we refer to Ref. \[21\]: Maxwell’s equations are integrated including retardation without scale approximations for given lightning channel base currents to yield the electric field \( \mathbf{E}(\mathbf{x}, t) \) and electromagnetic vector potential \( \mathbf{A}(\mathbf{x}, t) \) depending on time \( t \) and location \( \mathbf{x} \). Induced electric fields at location \( \mathbf{x}_o \) of a near observer (20-100 m horizontal distance from impact, level to perfectly conducting ground) are derived from the time derivative of the vector potential \( \mathbf{A}(\mathbf{x}_o, t) \) for various stroke types such as
leader, return strokes and M-components. For simplicity, cortical anisotropy and dielectric properties have been neglected in this work.

**Results: stimulation induced by successive return strokes**

We first consider straight vertical lightning channels using a leader model with a typical value for the homogeneous charge distribution of $q = 0.14 \text{ mC/m}$, and a current generation type model for the return stroke.

Our numerical calculations on subsequent multiple CG-dart leaders and return strokes show that in distances of the order of 20-100 m only the latter can induce above electric fields long enough to evoke perception: induced electric fields of dart leaders can in fact reach $E_{\text{ind}} > 20 \text{ V/m}$ above threshold, but the short dart leader pulse period of 2-3 $\mu$s (compared to TMS pulses of several 100 $\mu$s) may prohibit actual cognitive perception.

Return strokes are characterized by a fast rising phase and a slower decline phase of the nearby local magnetic field strength. The calculated pulse shapes of transcranially induced electric fields begin with a strong field peak in the order of kilovolts per meter and duration of microseconds caused by the large time derivative of the magnetic field in the short rise phase.

The action of this initial peak is difficult to predict due to the lack of comparably sharp field pulses in clinical brain stimulation. Assuming that the cell membrane of a single axon can be modelled as an RC circuit (i.e. a capacitance with a parallel connected leakage resistance) characterised by the cortical time constant of 150 $\mu$s, we can roughly estimate the resulting change in the membrane potential: The time dependent capacitor charging voltage of an RC circuit is given by $U(t) = U_0 (1 - \exp(-t/\tau))$ where $U_0$ is the applied voltage and $\tau$ is the time constant (i.e. the time taken by $U(t)$ to increase to 63% of $U_0$). Considering that a TMS induced electric field pulse of 20 V/m and 300 $\mu$s is able to trigger an action potential, we can deduce from the above equation that the initial field peak of a lightning return stroke ($E_{\text{ind}} \approx 2 \text{ kV/m}$, $t \approx 0.5\mu$s) leads to a membrane depolarisation which is $(2000 (1 - \exp(-0.5/150))) / (20 (1 - \exp(-300/150))) \approx 0.4$ times the depolarisation relative to the considered TMS pulse. Thus, an action potential could already be caused by this strong initial field rise phase peak of the return stroke.

The following long decline phase of return strokes LEMP s in the order of 200 $\mu$s has the most relevance for stimulation: our calculations for average discharge parameters show
FIG. 1: Electric field transcranially induced at various observation points (from bottom to top: 20 - 100m distance from strike point) by the time derivative of the lightning magnetic field during the decline phase of one average negative cloud-to-ground subsequent return stroke within a long high-multiplicity flash.

that in this phase LEMP induced potentials of the same order in amplitude and duration as rTMS pulses (larger than 20-50 V/m) occur in a distance less than around 100 m from the lightning channel. Results of the detailed simulations of this last phase of CG- return strokes are shown in Fig. 1 for various observer distances and otherwise standard parameters.

High multiplicity lightning, which has similar pulse repetition frequency as rTMS, can therefore be positively expected to stimulate cortical phosphenes for as long as several seconds. The observation of magnetophosphenes is actually not restricted to distances below 100 m, but may be experienced up to 300 m from the impact point, as strokes can occur with intensities (channel currents) up to 10 times larger than the average values used in our calculations.

Conclusion: likelihood to experience magnetophosphenes during a thunderstorm

In summary, we have calculated and analyzed the electric fields induced by all phases of near multiple lightning electromagnetic pulses, and have shown a remarkable agreement with fields induced by repetitive transcranial magnetic stimulation, which is known to cause
phosphene perception in observers when applied to the visual cortex.

The chance for transcranial stimulability of LEMP induced phosphenes can be roughly estimated. Occurrence of a repetitive stroke near to an observer (< O(200 m)) is essential to achieve an above threshold induction potential. Noticeable perception of phosphenes very likely occurs only when other sensory stimuli (or bodily injury of the observer) are not dominant. Direct observation of the blinding light and deafeningly loud thunder of lightning bolts may drown out phosphene perception. Magnetic fields of LEMP's are however able to penetrate walls and roofs, so that a direct line of sight to the bolt is not necessary to experience phosphenes.

Long perception in the order of seconds can be expected for the more rarely occurring repetitive strokes with multiplicity higher than 20, which occur for 1-5% of CG- strokes, although published statistics of such events are scarce [16]. As a conservative estimate, roughly 1% of (otherwise unharmed) close lightning experencers are likely to perceive transcranially induced above-threshold cortical stimuli. The activation by (time varying) weakly damped penetrating magnetic fields allows observation within closed buildings or aircrafts. Broadband stimulation of other sensory activity (odours, sound) can also be expected, but visual stimuli are usually dominantly perceived.

An observer reporting this experience is likely to classify the event under the preconcepted term of ”ball lightning”, which is used to subsume numerous reports on luminous perceptions during thunderstorm activity [4].

Here we conclude evidence for interpretation of a large class of ”ball lightning” observations as magnetic phosphenes transcranially stimulated by nearby long repetitive lightning strokes.

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Erratum and addendum

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In Ref. [1] the electric fields $\vec{E}_{\text{ind}}$ induced in the head of a nearby observer by natural lightning discharges (LD) were compared to laboratory transcranial magnetic brain stimulation (BS) fields and effects. In this respect an inappropriate assumption has been applied, that both $\vec{E}_{\text{LD}}$ and $\vec{E}_{\text{BS}}$ could be calculated by

$$\vec{E} = -\partial_t \vec{A},$$

which is valid if an electrostatic contribution $-\nabla \phi$ to the right hand side due to space charge accumulation can be neglected. In the following we show that this assumption is normally valid for BS but not for LD.

The vector potential $\vec{A}$ in the proximity of a straight vertical lightning channel is also directed vertically and its magnitude is decreasing with distance. In the case of a circular TMS field coil $\vec{A}$ is again oriented like the direction of the current flow, but here the current and therefore also $\vec{A}$ form closed loops inside the head, which are approximately parallel to the skull surface and do not necessarily cut through any surfaces. Hence there will be no charge accumulation (and hence no buildup of an electrostatic potential $\phi$), if the cortex is assumed to be an isotropic conducting medium.

Fig. 2 shows the direction of components of $\vec{E} = -d\vec{A}/dt$ projected onto a ”quadratic loop” inside the head. For clinical brain stimulation, the components form a closed loop (”BS”, left figure part), while for a lightning magnetic field there is a net contribution from one corner to its opposite on the loop (”LD”, right part).

If, as it is the case for lightning fields, the vector potential does cut a surface (of the cortex or the skull), across which there are two media of different conductivity, there will be charge accumulation on the surface. This will cause a non-zero scalar potential $\phi$ which must be included in calculating the total electric field. However, in the complex geometry of the different conducting media in the head an exact calculation is a highly nontrivial task.
More generally, the electric field $\vec{E}(t)$ induced by a time varying magnetic $\vec{B}(t)$ field is calculated from the Maxwell-Faraday equation $\nabla \times \vec{E} = -\partial_t \vec{B}$ so that

$$U_{\text{ind}} = \oint \vec{E} \cdot d\vec{l} = -\partial_t \int \vec{B} \cdot d\vec{S} = -\partial_t \psi$$

(2)
corresponds to the voltage induced in a loop surrounding an area $S$, enclosing the magnetic flux $\psi$. The average electric field along the loop can be calculated by $\langle E \rangle = U_{\text{ind}}/L = \partial_t \psi/L$ where $L = \int d\vec{l}$.

![FIG. 2: Electric fields around a quadratic loop due to the vector potential of a brain stimulation coil (left) and the vector potential of a lightning channel pointing in $z$-direction (right).](image)

In the literature concerning clinical BS (e.g. Ref. [2]), eq. (1) is used to compute $E_{\text{ind}}^{BS}$. In Ref. [1] we therefore used expression (1) as a reference quantity for the comparison of $E_{\text{ind}}^{LD}$ and $E_{\text{ind}}^{BS}$. Eq. (1) indeed corresponds to $E_{\text{ind}}^{BS}$ when it is applied to brain stimulation coils. $E_{\text{ind}}^{LD}$, however, is different from eq. (1) because of the different spatial variation of the vector potentials $\vec{A}^{LD}$ and $\vec{A}^{BS}$ in the area of integration, as is shown in the following.

First consider $E_{\text{ind}}^{BS}$, induced by the magnetic field of a brain stimulation coil with current loops located close to the head. For simplicity a quadratic loop, shown in the left part of Fig. 2 with side length $l$ is assumed. Thus, the vector potential $\vec{A}^{BS}$, and with it the electric field $\vec{E} = -\partial_t \vec{A}^{BS}$, forms closed loops. For the given loop this yields $A_{x}^{BS}(z) = A_{x}^{BS}(z + l) = A_{x}^{BS}(x) = A_{x}^{BS}(x + l) = A^{BS}$, and the voltage induced in the loop can be expressed as $U_{\text{ind}}^{BS} = -\int \vec{E} \cdot d\vec{l} = \partial_t \int \vec{A}^{BS} \cdot d\vec{l} = 4l \partial_t A^{BS}$. This results in $E_{\text{ind}}^{BS} = -U_{\text{ind}}^{BS}/(4l) = -\partial_t A^{BS}$ which corresponds to eq. (1).
Regarding the lightning case, a straight and vertical lightning channel pointing in z-direction and an observer on perfectly conducting ground may be assumed, so that the vector potential $A^{LD}$ has a vertical component only. Consider the quadratic loop shown in the right part of Fig. 2. Due to the small $x$-dependence of $A^{LD}$ we now have $A^{LD}_z(x) \neq A^{LD}_z(x+l)$, and the voltage induced in the loop is given by $U^{LD}_{ind} = -\int \vec{E} \cdot \vec{dl} = \partial_t \int A^{LD} \cdot \vec{dl} = l \partial_t \left[ A^{LD}_z(x) - A^{LD}_z(x+l) \right] = -l^2 \partial_t \partial_x A^{LD}_z$ resulting in $E^{LD}_{ind} = -U^{LD}_{ind}/(4l) = (l/4) \partial_x \partial_t A^{LD}_z$ which is different from eq. (1).

Consequently, $E^{LD}_{ind}$ can not be computed by eq. (1) but has to be calculated from eq. (2). For $E^{BS}_{ind}$ eqs. (1) and (2) yield the same result. Due to the incorrect use of eq. (1) the results for lightning induced electric fields obtained in Ref. [1] for average lightning parameters are more than an order of magnitude too large (depending on distance). Correct results for $E^{LD}_{ind}$ and their consequence on the probability of cortical and retinal phosphene stimulation using eq. (2) are discussed in the following.

We now do not focus on one specific (average) lightning channel base current and waveform like in Ref. [1], but rather explore a range of above average but still usual parameters. It turns out that fields induced by the previously considered long current decline phase of return strokes (order of 100 $\mu$s) are below known cortical phosphene thresholds for the range of considered lightning parameters at relevant distances (i.e., more than several meters, where other lightning effects and injury may not be expected to be dominant on an observer).

We therefore now also reconsider the possibility of an effect of the return stroke current rise phase on cortical axon stimulation. Fig. 3 (top) shows the initial rise phase for different channel base current waveforms $I(t)$ of return strokes, and Fig. 3 (bottom) shows the corresponding associated maximum values of the induced electric fields $E^{LD}_{ind}$ for different distances from the lightning channel. $E^{LD}_{ind}$ is calculated from the time varying magnetic flux through a circular area with a cortex radius of 0.07 m. The figure shows that the maximum value of $E^{LD}_{ind}$ is mainly determined by $\partial_t I$. The cortical phosphene threshold of around $20 - 40$ Vm$^{-1}$ is exceeded in distances up to order of 50 m for return strokes that are characterised by a current rise of $\frac{dI}{dt} \gtrsim 100$ kA $\mu$s$^{-1}$. The duration of a single induced electric field pulse is determined by the current rise time (0.5 – 5 $\mu$s) and repeated with the frequency of multiple strokes.

It is however not evident if these short pulses in the rise phase in the order of microseconds actually allow stimulation of phosphenes, as no clinical experience with similar pulse forms
is available. In vitro experiments suggest that to fire axons may require longer exposure (> 100 µs) to electric fields of similar strength \[4\]. Stimulation of cortical phosphenes by multiple lightning return strokes therefore appears improbable for relevant parameters and distances above several ten meters.

On the other hand, it had already been noted in Ref. \[1\] that retinal phosphenes have a much lower threshold than their cortical counterparts \[3\], which is according to Refs. \[5, 6\] in the range of \(10^{-3} - 100\) mV m\(^{-1}\). The feasibility to stimulate retinal phosphenes with lightning induced electric fields is therefore much higher than for cortical phosphenes. In Ref. \[1\] we expressed the point of view that when lightning induced cortical phosphenes can be shown to possibly exist, then retinal phosphenes are an even more likely event under the same circumstances. As lightning induced stimulation of cortical phosphenes has now been shown to be much less probable, we also re-evaluate the possibility of retinal phosphenes by means of the corrected calculations: Indeed \(E_{ind}^{LD}\) can reach above retinal phosphene threshold values at distances up to order of 50 m from the lightning channel also during the long return stroke decline phase of \(100 - 200\) µs pulse duration, and in even considerably longer distances (order of 200 m) during the short rise phase.
Unfortunately no directly comparable specific retinal stimulation experiments could be found in the available literature. While the average frequency of return strokes in a multiple lightning discharge (20 Hz) coincides with the repetition frequencies usually used in retinal stimulation experiments, the pulse shapes of $E_{\text{ind}}^{\text{LD}}$ and $E_{\text{ind}}^{\text{RS}}$ considerably differ [5]: usually, the retina is stimulated by sinusoidal waveforms with a frequency of also $20 - 45$ Hz by TMS, compared to return stroke pulse durations of several $100 \mu s$. Studies on direct current electrical excitation of the human retina however indeed show stimulability for short pulse durations of $250 \mu s$ [7]. The possibility of stimulation of retinal phosphenes by lightning fields could of course in future be verified by physiological investigations using comparable magnetic pulse forms.

An experimental setup which covers both retinal and cortical stimulation regions may indeed easily be devised with a pair of Helmholtz coils with radius and separation larger than a human head, where currents are applied that directly generate nonfocal magnetic fields with strengths and pulse shapes as calculated for realistic lightning conditions in various distances. This suggested experimentum crucis is able to critically test the lightning electromagnetic phosphene stimulation hypothesis.

In spite of the previous overestimation of induced electric fields in Ref. [1], a stimulation of phosphenes induced by lightning electromagnetic pulses remains plausible. The most probable site of stimulation however appears to be the retina rather than the visual cortex.

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