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Human Postural Control Under High Levels of Extremely Low Frequency Magnetic Fields

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ABSTRACT *Background*: International agencies such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the International Committee on Electromagnetic Safety (ICES) of the Institute of Electrical and Electronics Engineers (IEEE) need further data to set international guidelines to protect workers and the public from potential adverse effects to Extremely Low-Frequency Magnetic Fields (ELF-MF). Interestingly, electromagnetic induction has been hypothesized to impact human vestibular function (i.e. through induced electric fields). To date, a theoretical 4 T/s vestibular threshold was proposed to modulate postural control, but data is lacking above this limit. *Objectives:* This research aimed to investigate the impact of full head homogeneous ELF-MF stimulations above the 4 T/s threshold on human postural control. *Methods*: Postural control of twenty healthy participants was analyzed while full head homogeneous ELF-MF stimulations (20 Hz, 60 Hz, and 90 Hz) up to 40 T/s were applied. Velocity, main direction and spatial dispersion of sway were used to investigate postural modulations. *Results*: Despite a conclusive positive control effect, no significant effects of ELF-MF exposures on velocity, spatial dispersion, and direction of the postural sway were found for our 3 frequency conditions. *Conclusions*: The homogeneous full head MF stimulations oriented vertically and delivered at high frequencies induced E-fields having a weaker impact than anticipated, possibly because they impacted only a small portion of the vestibular system. This resulted in an absence of effect on postural control outcomes.

INDEX TERMS Electromagnetic induction, Extremely Low-Frequency Magnetic Fields (ELF-MFs), human vestibular system, postural control.

I. INTRODUCTION

Extremely Low-Frequency Magnetic Fields (ELF-MFs < 300 Hz) at powerline frequencies (i.e 60 Hz in North America) are ubiquitous in modern societies due to the generation, distribution and use of alternating current (AC). From a health and safety perspective, agencies such as the International Commission for Non-Ionizing Radiation Protection (ICNIRP) and the International Committee on Electromagnetic Safety from the Institute of Electrical and Electronics Engineers (IEEE-ICES) depend on reliable scientific data to set guidelines and recommendations [1], [2], to protect workers and the general public against electrostimulation induced adverse health effects.

In this regard, the latest IEEE-ICES standards state the necessity to investigate established acute mechanisms capable of synaptic activity alterations [2]. The most reliable effect of synaptic polarization is the acute perception of magnetophosphenes. Magnetophosphenes are flickering visual manifestations perceived when exposed to a sufficiently strong ELF-MF [3]. Therefore, the ICNIRP and the IEEE-ICES report synaptic activity alterations thresholds based on Saunders and Jefferys [4] and Lövsund *et al.* [5] magnetophosphenes studies.

Magnetophosphenes are reported to result from the modulation of the retinal cells [4]–[6]. Since the retina is

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recognized as an integrative part of the Central Nervous System (CNS), magnetophosphenes are considered as a good conservative model to be generalized to the entire CNS [6].

In the vestibular system, the mechanical information of head movements is transduced into an electric signal via sensory cells called hair cells. Compellingly, both the vestibular system and the retina use graded potential sensory cells [7] known for their high sensitivity mainly due to the continuous release of glutamate through ribbon synapses [8]–[11]. Moreover, as retinal cells [6], [12], vestibular hair cells are known to be easily impacted by weak electrical currents [13]–[17]. Therefore, vestibular hair cells also appear as perfect targets for interaction with ELF-MF induced currents.

Consequently, from the perspective of the guidelines, the investigation of ELF-MF on the vestibular system is legitimate, as it would broaden the understanding of the underlining mechanisms enabling to better understand how phosphenes could be generalized to the entire CNS. Individuals around Magnetic Resonance Imaging (MRI) scanners often report illusions of rotating, vertigo, dizziness, and nausea, suggesting an interaction between MF and the vestibular system [18]–[20]. In 2007, Glover *et al.* [21], published a seminal study on the interactions between static and time-varying MF and the vestibular system. They identified three different mechanisms possibly responsible for vestibular responses to MF exposure: i) the Diamagnetic Susceptibility (DS), ii) the Magneto-HydroDynamic (MHD) forces and iii) the Electromagnetic Induction (referred as induction herein). The DS hypothesis has been consistently dismissed as negligible, in both theoretical and experimental works [21]–[24]. Conversely, MHD forces have been reported to modulate the vestibular system in a strong static magnetic field (SMF) environment. Indeed, a strong oriented SMF generates a Lorentz force that triggers nystagmus through activation of the Vestibulo-Ocular Reflex [22]–[25]. However, MHD does not apply in an SMF-free environment. The third hypothesis of interaction is the induction mechanism based on Faraday's law of induction, stating that changing magnetic flux density over time (dB/dt in T/s) induces Electric Fields (E-Fields) and currents within conductors such as the human body. Indeed, besides magnetophosphenes, effects resulting from magnetic induction in humans have been reported on the central nervous system [4], [26]–[31], the autonomous nervous system [32]–[34], and the peripheral nervous system [35].

In their "static subject changing field" experiment, Glover *et al.* [21] proposed a formal attempt to test if ELF-MF induction modulates vestibular performance. They showed no effect of a 2 T/s ELF-MF on human postural control, but they still hypothesized that stimulation over 4 T/s should be able to trigger a vestibular response [21].

Consequently, our work furthers the investigation of postural responses using full head homogeneous ELF-MF stimulations with high dB/dt, up to 40 T/s with the main objective to study vestibular outcomes at power frequency (60 Hz). Since the magnitude of vestibular outcomes increases linearly with current intensity [36]–[38], we expected to observe an increase in postural modulations with higher dB/dt values.

II. METHODS

A. PARTICIPANTS

Twenty healthy participants (6 females - 14 males, 23.5 ± 3.68 years old) were tested. We excluded volunteers with a history of any vestibular-related dysfunction, chronic illnesses, neurological diseases, and participants having permanent metal devices above the neck. Participants had to refrain from exercise and alcohol, caffeine or nicotine intake 24 hours before the study.

FIGURE 1. Stimulation apparatus. Volunteers stood in complete darkness, feet together, arms by their side and eye closed on a 1.5 cm foam pad covering the force plate. Their head was fully stimulated by Helmholtz-like coils centered on their ears, with ELF-MF stimulations at 8.89 T/s, 26.66 T/s and 39.98 T/s (left panel). The binaural bipolar DC montage stimulating both vestibular systems at 2 mA. The cathode is behind the right mastoid process and the anode is behind the left mastoid process (right panel).

B. EXPERIMENTAL DEVICES

ELF-MF stimulations were delivered to the subjects' head via a customized head coil exposure system (Fig.1 left panel) consisting of a pair of 99-turn coils (11 layers of 9 turns each, 35.6 cm inner diameter and 50.1 cm outer diameter) made of hollow square copper wire cooled by circulating water. The two coils were assembled into a Helmholtz-like configuration, spaced 20.6 cm from center to center. The system was controlled and data was collected using a custom LabVIEW^{TM}script (LabVIEW 2014 version 14.0.1 (32 bit)) through a 16-bit National Instruments A/D Card output channel (National Instruments, Austin, TX), driving two MRI gradient amplifiers capable of delivering up to 200 A at ±345 V (MTS Automation Model No. 0105870, Horsham, PA, USA). A Biot-Savart model of our custom coil system was computed using a customized Matlab program (MatLab version 9.3 – The MathWorks Inc., USA) considering two systems of 11 solenoids of 9 turns stacked on each other following the geometrical characteristics presented above.

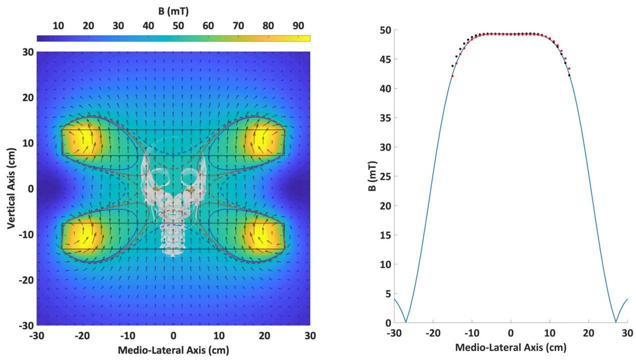

FIGURE 2. 2-D spatial illustration of the MF level distribution around the exposure system computed according to the Bio-Savart law (Left panel). The thick black rectangles represent the outer boundaries of both coils. Small black arrows represent the magnetic vector field. Red and blue lines represent respectively the boundaries of a 1% and 5% flux density variation limit area from the center. Dashed lines represent the lower boundary while solid lines represent the upper boundary. Participants' vestibular systems, illustrated by the yellow structures in the head, lie within a 50 mT (±0.5 %) vertically- oriented homogeneous field. Flux density values for full head homogeneous ELF-MF stimulations targeted at 50 mT (right panel). The blue line represents the expected flux density values given by the model along the mediolateral axis. Red and black dots are actual flux density measurements along the mediolateral and anteroposterior axes respectfully.

This model presented in Fig.2 shows the homogeneity of the magnetic field at the location of the participant's head. MF flux densities measurements were recorded every centimeter from the center of the coil in both the Antero-Posterior (AP) and Medio-Lateral (ML) axes (Fig.2 right panel) with a single axis MF Hall transducer probe (± 200 mT range with 0.1% accuracy, Senis AG Model No. 0YA05F-C.2T2K5J, Baar, Switzerland). These measurements showed great agreement with our model (Fig.2 right panel). During the experiment, the probe was located 16 cm from the center of the coils, and data were recorded and used to synchronize all measurements with MF expositions. A force plate (OR6-7-1000, AMTI, USA) was used to collect participant's body sway at 1 kHz according to 6 degrees of freedom: forces and moments data each in the 3 dimensions. The Center of Pressure (COP) trajectory was calculated post-recording using a calibration matrix provided by the manufacturer. No hardware filtering was applied. A motorized non-magnetic lift enabled vertical movement of the coil system, such that it could raise and lower, centering the participants' ears between the coils (Fig.1 left panel). A Direct Current (DC) stimulation was delivered using a transcranial current stimulation device (StarStim, Neuroelectrics, Spain), controlled with the NIC software (Neuroelectrics Instrument Controller, version 1.4.1 Rev.2014-12-01) via Bluetooth.

C. PROTOCOL

After giving written informed consent, participants were equipped with the Starstim device. A DC stimulation was used as a positive control condition to validate the choice of our dependent variables. Positive control is defined herein as a condition in which specific known effects are expected [39]. Indeed, based on the scientific literature, DC is known to increase the postural sway, specifically oriented towards the anodal side of the stimulation (for review see [40]). In this regard, a classical binaural bipolar montage was used (Fig.1 right panel). Both mastoid processes were previously rubbed with alcohol wipes (Mooremedical, USA) to improve impedance. Circular 25 cm^2 Ag/AgCl electrodes (StarStim, Neuroelectrics, Spain) were saturated with 8 mL of saline solution to provide proper conduction. Electrodes were secured using the StarStim neoprene cap and tape. To ensure appropriate stimulations, electrode impedances were maintained below 10 kΩ throughout the experiment as recommended by the manufacturer. The cathode was placed behind the right ear. Before starting the testing, the participants were exposed to a 5 seconds 2 mA DC exposure as a familiarization sample and to make sure they all swayed towards the anodal side [40]. Participants were then asked to stand still, in complete darkness, during 20 seconds on a 1.5 cm thick foam surface arranged over the force plate with their eyes closed, arms along the sides and feet together to sensitize the vestibular system [40]. Participants heads' stayed within the ELF-MF stimulation system at all times during the trials (Fig.1 Left panel). A second investigator, blinded to the type of stimulation, was present to prevent potential loss of balance.

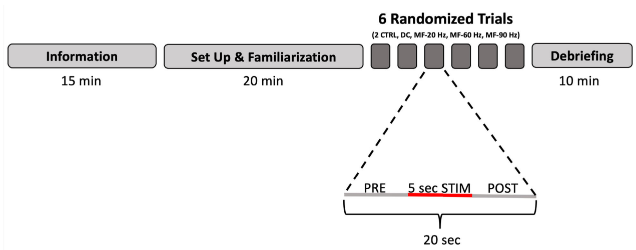

FIGURE 3. Schematic representation of the postural control protocol.

Following a repeated measure plan, we presented four types of stimulations in a random order to all our participants. One DC (2 mA) and three MF (50 mT) exposures were all delivered for 5 seconds. To reach high levels of dB/dt, we chose to modulate the exposure frequencies instead of exposure flux density. In the ELF range, the highest synaptic sensitivity occurs at 20 Hz [2], a frequency also known to induce vestibular modulations [41]. Moreover, since vestibular electrical stimulations up to 100 Hz have shown to impact the vestibulospinal pathways [42], we decided to stay within these boundaries and investigated 90 Hz. Therefore, 20, 60, and, 90 Hz respectively produced 8.89 T/s, 26.66 T/s, and 39.98 T/s, two to tenfold higher than the 4 T/s threshold. Two control trials (CTRL) without stimulation were also done for each participant. All trials were randomly distributed. Thirty-second rest periods were taken between each trial. A timeline of our experiment is presented in Fig.3. To prevent postural outcomes bias due to cerebrovascular alterations participants could not sit during rest [43]. To conceal the noise generated

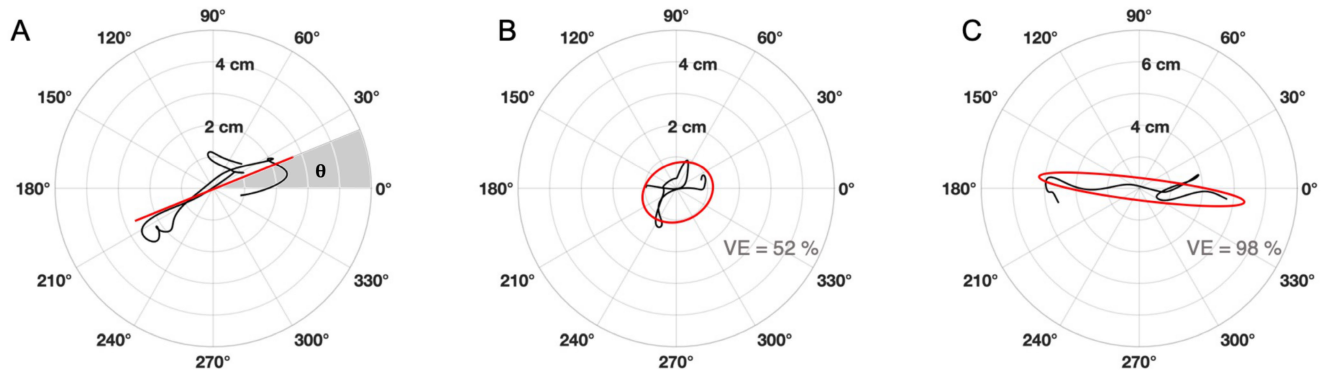

FIGURE 4. **Graphical representation of dependent variables found with Principal Component Analysis. In all panels, the movement of COP is represented by the black line. In A, the red line represents the main direction of sway at an angle θ symbolized by the grey shaded area. A direction of sway at 90 degrees angle would indicate a pure AP sway. In B and C red ellipses are examples of dispersion of the orientation of sway in space. In B, 52 % of the variance explained is expressed along the first PC whereas, in C, 98 % of the variance explained is expressed along the first PC.**

by the coils, subjects wore earplugs throughout the experiment. This protocol was approved by the Health Sciences Research Ethics Board (#106122) at Western University.

D. DATA ANALYSIS

The COP time-series were filtered with a low pass bidirectional 4^{th} order Butterworth zero-phase digital filter with a cutoff frequency of 5 Hz. Cutoff frequency was determined after a residual analysis using a customized Matlab program. Sway characteristics were also computed using a customized Matlab program. Classically sway variables are analyzed on orthogonal AP and ML axes independently. However, our participants were put in unconventional conditions to sensitize vestibular function and AP-ML analyzes are known to be biased by biomechanical factors [36]–[38]. Secondly, AP and ML data are not independent as balance is controlled by coordinating the body in space in both dimensions simultaneously [46]. Finally, anatomical [47] and/or physiological [48] asymmetries between the two vestibular systems could induce subtle angular deviations not purely found along the classical AP-ML axis. Therefore planar sway analyzes were favored over one-dimensional analyses. Among classical sway variables, the pathlength (the total length of COP excursion) has proved to be the more sensitive and reliable outcome [41], [42]. Pathlength was computed as the total sum of the distances between each point in the AP-ML plane. However, because pathlength varies with recording data time it is often hard to compare results from one study to another. Therefore, mean velocity (pathlength over time) was retained.

A Principal Component Analysis (PCA) was conducted on COP datasets to find the main direction of sway [51] (Fig. 3). The main direction of sway is described by the first principal component (PC1) which accounts for the largest part of the COP time-series' variance. $\boldsymbol{\theta}$, the angle between the ML axis and the PC1 axis was computed to describe the main direction of sway (Fig.4A). $\boldsymbol{\theta}$ was always presented within 0° and 180°, regardless of the direction of the movement towards the right or the left: 0° being aligned with the ML axis toward the right side of the participant. The second principal component (PC2) represents the axis orthogonal to PC1. PC1 and PC2 can be used to compute the 95% confidence interval ellipse of the sway for each trial [51] (Fig.4B and 4C). Each PC expresses a certain percentage of the total variance of the data. The percentage of variance explained (VE) by PC1 was used to analyze how the sway was dispersed in space. Indeed, as VE of PC1 approaches 100%, the ellipse merges closer to PC1 itself, thus expressing less spatial dispersion (Fig.4 C). Likewise, VE closer to 50% would indicate that the total variance is gradually equally shared by PC1 and PC2 indicating a dispersed sway bounded by a circle (Fig.4 B).

To investigate the acute effects of DC and MF, the sway responses were all analyzed during the first 2 seconds after stimulation onset within which the peak postural response for DC was found and reported in previous work [52].

E. STATISTICAL ANALYSIS

All statistical analyses were performed using R version 3.3.2 [53]. A level of significance of $\alpha = 0.05$ was adopted throughout data analysis. Percentages were not normally distributed, therefore, a logarithmic transform was used for VE.

One set of control data was randomly chosen and used to compare the effect of DC while the other set was used in contrast to MF stimulations. To investigate the effect of DC stimulations (DC vs CTRL), paired t-tests were used to analyze mean velocity as well as VE. To explore the effect of frequency on mean velocity as well as on VE, the data were analyzed by one-way repeated-measures ANOVAs with frequency (CRTL+ the 3 frequencies modalities) as the within-subject variable.

For $\boldsymbol{\theta}$ analyses, circular statistics were used using the circular library in R. Using Rayleigh's test for uniformity of the distributions, we first ensured that $\boldsymbol{\theta}$ data samples were not distributed uniformly. Mean $\boldsymbol{\theta}$ and Angular Deviation (±AD) were used to describe the main direction of sway.

A Watson-Williams two-sample test was used to investigate the effect of DC on the direction of the sway. A Watson-Williams multi-sample test was used to investigate the effect of frequency on the direction of the sway [54].

III. RESULTS

A. DC STIMULATIONS

The effect was unambiguous and reflected previous findings. Systematic loss of balance towards the anodal side was observed. Table 1 shows that both velocities (t (19) = 5.1398, $p < 0.001$, $r^2 = 0.58$) and VE (t (19) = 2.91, $p < 0.05$, $r^2 = 0.30$) were significantly greater during DC than without. However, θ did not change with DC (F (1,38) = 0.48, p = 0.49) and stayed generally aligned along ML.

TABLE 1. Descriptive statistics for the DC results (CTRL vs DC). Mean and standard errors (± SE) values for velocities and variance explained as well as mean angles and angular deviations (± AD) for Theta.

	CTRL	*DC*
*Velocity (cm/s) ****	2.5 ± 0.3	5.3 ± 0.6
*Variance Explained (%) **	82.3 ± 2.6	91.6 ± 2.1
Theta (°)	- 8.7 ± 39.5	- 0.3 ± 31.2

CTRL : Control Condition ; DC: Direct Current condition

* p < 0.05 for paired t-test comparing CTRL and DC

*** p < 0.001 for paired t-test comparing CTRL and DC

B. ELF-MF STIMULATIONS

No significant differences between frequency of MF stimulation were found on Velocity (F (3,57) = 1.26, p = 0.29, Fig.5A) nor on VE (F (3,57) = 0.42, p = 0.73, Fig.5B). Similarly, no significant differences were found for θ (F (3,76) = 1.52, p = 0.21) between the frequency conditions. The Fig.6 shows majorly sways along the ML axis with a circular mean of −0.77° for all conditions.

C. PHOSPHENE PERCEPTIONS

Out of the 20 participants, 13 (65%) declared seeing phosphenes at least once during the entire experiment.

IV. DISCUSSION

Given the very important neurophysiological similarities between the retinal and the vestibular sensory cells and the fact that electromagnetic induction produces magnetophosphenes, this study aimed to investigate the impact of full head 50 mT homogeneous ELF-MF stimulations at 20 Hz, 60 Hz and 90 Hz on human postural control in which the vestibular system plays a major role.

We replicated the "Static Subject Changing Field" experiment from Glover et al. [21] with a greater number of participants, more sensitive postural outcomes measures at higher dB/dt values than their 4 T/s vestibular threshold.

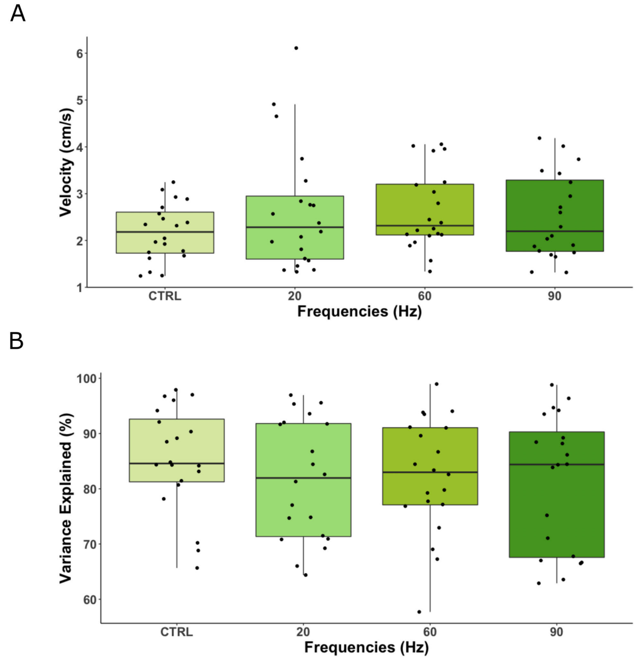

FIGURE 5. Mean velocities (A) and variance explained (B) for CRTL vs all MF experimental conditions. Error bars represent 95% confidence intervals.

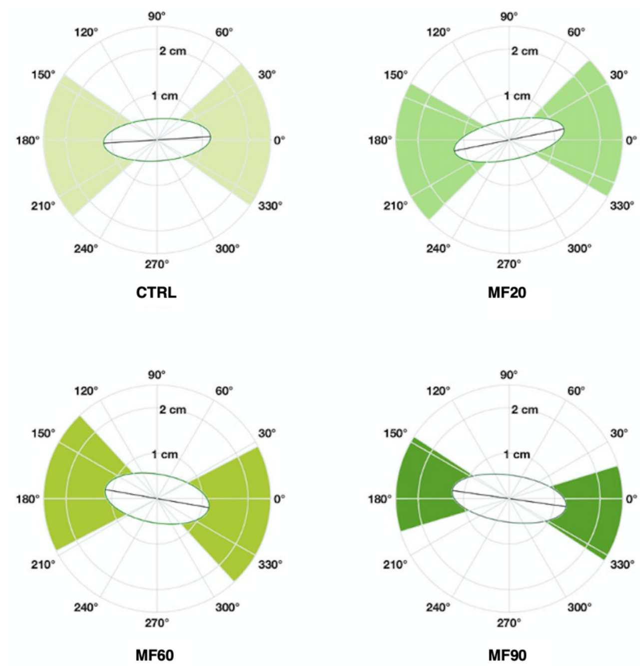

FIGURE 6. Average sway orientation for CRTL vs all MF experimental conditions. The black lines represent the main direction of sway (PC1) at the angle θ. The length of each black line is proportional to the mean quantity of movement expressed by the participants. Ellipses are a representation of the mean area of COP displacement. Shaded areas from light green (CRTL) to dark green (90 Hz) represent the angular deviation as frequency increases.

First, the use of a DC stimulation enabled us to validate the postural variables chosen in this work. As predicted, DC increased the quantity of movement. Indeed, greater velocity values characterized the loss of balance experienced by all participants. Similarly, increased sway alignment shown by greater VE values and the direction angles along the mediolateral axis portrayed the well-known DC-induced movements directed towards the anodal side in the frontal plane (for review see [40]).

Contrary to our hypothesis, our findings showed no postural response to ELF-MF stimulations despite being up to tenfold above Glover's 4 T/s threshold. Indeed, in our study, peak dB/dt levels reached 8.89 T/s, 26.66 T/s, and 39.98 T/s at 20 Hz, 60 Hz, and 90 Hz respectively. For their international guidelines and standards, ICNIRP and IEEE-ICES need in-situ E-Field threshold assessments to which uncertainty and safety factors are applied to fully protect the public as well as the workers [1], [2]. These publications estimate *in-situ* E-fields using Maxwell equations applied to an ellipsoid model [55], but have acknowledged later that anatomical models could also be used [2]. Nonetheless, it is acknowledged that good estimations of *in-situ* E-fields are also obtained with analytical spherical models [56]. Therefore, we estimated the *in situ* induced E-Field generated by our stimulations, with the following Maxwell equations:

$$E = \frac{r}{2}\frac{\partial B}{\partial t} = \pi r f B \quad (1)$$

where E represents the induced E-Field and r the radius of the Faraday's loop within a homogeneous alternating flux density B of frequency f. Given a 5 cm radius loop encompassing both vestibular systems (Fig.7), the 4 T/s threshold presented by Glover *et al.* [21] would produce 0.1 V/m tangentially to that loop. Following the same reckoning our stimulation would produce peak E-field at 0.225 V/m, 0.65 V/m, and 1 V/m for our respective frequencies at the level of the vestibular systems. Despite having E-field values twice to ten times higher than the theoretical threshold estimated by Glover *et al.* [21], no differences in the quantity of movement, spatial dispersion nor on the direction of sway were observed.

In this light, several key points should be addressed to understand the absence of postural response: i) the role of the frequencies of stimulation used to reach high dB/dt values, ii) the role of the orientation of the MF, and finally iii) the anatomy and physiology of the vestibular structures impacted.

First, stimulation frequencies of 20 Hz, 60 Hz, and 90 Hz were chosen to generate dB/dt levels theoretically capable of triggering vestibular responses.

Importantly, in the case of electrical stimulation of the vestibular system, it is considered that postural outcomes are mostly due to semicircular canal activation (for review see [57]). Moreover, with alternating signals, as stimulation frequency increases, the weight of the otolithic input increases while the weight of the canalithic input decreases [58]. As a consequence, the high frequencies used in our study may have mainly impacted the otoliths, potentially yielding to weaker postural modulations.

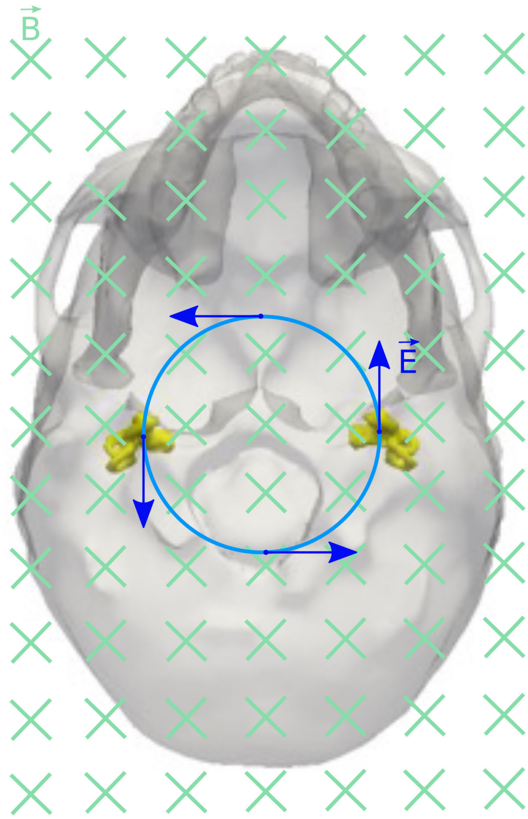

FIGURE 7. Bottom view of field orientation within a head representation. Both yellow structures are the vestibular systems. The green crosses represent the homogeneous MF increasing towards the top of the head. The light blue circle symbolizes a 5 cm radius Faraday's loop encompassing both vestibular systems. The dark blue arrows represent the tangential induced E-fields generated at selected points of the loop.

Second, since the otoliths were the most likely impacted targets of our magnetic stimulations, their relative orientation to the induced fields must be considered. The otolithic subsystem is composed of the utricle and the saccule, which are responsible for detecting head horizontal and vertical linear accelerations respectively. The utricle is mostly planar, lying in the horizontal plane, whereas the saccule is mostly planar, lying orthogonally in the vertical plane. Given the orientation of both utricles and saccules in space, their respective vestibular hair cells would predominately be crossed perpendicularly by the induced E-fields. Considering that only E-Fields colinear to the body of the neuronal cells have a maximum impact [59], only a fraction of the induced E-fields could have influenced the otolithic hair cells. Therefore, considering that the induced E-Field threshold to modulate vestibular function was indeed met, its alignment relative to sensitive target cells (hair cells) may not have been optimal to allow a functional response.

Finally, anatomically both saccules' and utricles' maculae are divided by a striola. On each side of the striola, the vestibular hair cells are oppositely disposed, such that for any imposed head acceleration, one side will be excited while the other side will be inhibited [40], [60]. Considering such cross-striolar inhibition mechanisms [61], any impact of induced E-fields and currents on oppositely oriented hair cells would be reduced within each otolithic sub-systems, on each side of the head [40]. Consequently, little net vestibular signals would only be generated and integrated.

In summary, i) the use of high frequencies limited the postural responses by favorizing the otolithic over the canalithic system ii), only a fraction of induced E-Field influenced the otolithic hair cells, and iii), this remaining fraction of induced E-Field was subjected to the cross-striolar inhibition mechanism in both utricular and saccular maculae which further limited the effect on postural control.

Interestingly, studies using 0.7 T/s 60 Hz ELF-MF stimulations orthogonal to ours, have observed an impact on human postural control [62]–[65]. However, these results should be interpreted with caution. First, the dB/dt value was far below the theoretical 4T/s threshold. Second, the whole body was exposed and, therefore, the effects could have resulted from other sensory and/or motor modulations. Nonetheless, the suggestion of the crucial effect of the orientation of the field orientation can also be found in the magnetophosphene literature. Indeed, magnetophosphenes thresholds can vary 2.5 fold depending on field orientation [56]. Considering Lövsund *et al.* [66], Lövsund *et al.* [67], in which the fields exposed the participants' head laterally, the 2019 IEEE ICES standards [2] report a magnetophosphenes threshold at 20 Hz to be at 0.075 V/m peak. Yet considering Hirata *et al.* [56], this threshold could be lowered to 0.04 V/m peak when the field is orientated vertically. While vertical magnetic fields are well suited to impact retinal cells, lowering the magnetophosphenes thresholds [56], the same field orientation is, as seen in our results, ineffective on the vestibular hair cells. Furthermore, the vestibular systems, being more deeply nestled within the skull than the eyes, the Faraday's loop encompassing both vestibular apparatuses, is smaller than the loop enclosing both eyes. Therefore, the E-fields at the vestibular system level are smaller than at the retinal level. However, with our MF at 20 Hz, an E-field of 0.225 V/m is induced at the vestibular system level, which is more than 5 times stronger than the 0.04 V/m peak phosphene threshold calculated by Hirata *et al.* [56] with the same field orientation. It is also 3 times stronger than the 0.075 V/m peak estimated head exposures threshold of the guidelines [2]. This indicates that with the dB/dt values reaching 40 T/s in the current study, the induced E-fields for the retina and/or the CNS were above the threshold values used as bases in the guidelines and recommendations. Despite induced E-fields exceeding the electrostimulation threshold values from the guidelines, no sensorimotor effects, besides phosphenes, were found in our study. Therefore, given the close neurophysiological similarities between vestibular hair cells and retinal cells, the absence of postural modulation showed by our results could challenge the idea of generalizing the threshold from retinal effects to the entire CNS. Indeed, our results suggest that the generalization based on neurophysiological similarities may not be appropriate. It is important to keep in mind that field orientation and structure localization in the CNS are also important parameters playing a role in the ability of an external MF to induce effective neurostimulation. Yet, such considerations would greatly benefit from specific dosimetry work concerning the vestibular system, which is still lacking to date.

It is also important to keep in mind that the main objective of this work was to study the potential effect of a whole head exposure to a power-frequency MF on postural outcomes. In these specific conditions, it was hard to control for magnetophosphenes' perception, which has to be acknowledged as a possible confounding factor. This is however unlikely since body sway recordings during flickering light perceptions with frequencies above 16 Hz do not significantly differ from recordings with uniform room illumination [68], suggesting that magnetophosphenes perception would not have modulated postural outcomes. Yet full adaptation to darkness could reduce phosphene perception and help to better control such factors [69].

V. CONCLUSION

Our study suggests that before a formal investigation of the level for an acute postural response to ELF-MF, further research should address the difficulty of specifically targeting the vestibular system. Furthermore, more parameters such as MF orientation and frequency as well as vestibular anatomical and neurophysiological specificities need to be taken into consideration. Complementarily, more specific and potentially more responsive vestibular outcomes such as vestibular related eye movements or neck muscle activation should be thoroughly studied [42], [70]–[72] to conclude on the significance and importance to study the impact of induction on the vestibular system within the frame of the guidelines.

Nonetheless, given the favored anatomical location of the retina, the fact that there is no inhibition mechanism at its level compared with the vestibular system, and the sensitivity of the retinal receptors, phosphenes remain to date the most sensitive response to ELF-MF stimulations. Therefore, to protect against potential adverse reactions associated with induced electrostimulation and to stay conservative, phosphenes should remain the basis of the international guideline.

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