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Impact of Vestibular Stimulation at Powerline Frequency on Human Pointing Accuracy

Nicolas Bouisset[1,2], Andres Carvallo[3], Perrine Dumur[3], Sofiane Ramdani[4], Alexandre Legros[1,2,3,5,6*]

[1] Human Threshold Research Group, Lawson Health Research Institute, London (ON), Canada
[2] School of Kinesiology, Western University, London (ON), Canada
[3] EuroMov Digital Health in Motion, Univ Montpellier, IMT Mines Ales, Montpellier, France
[4] LIRMM, Université de Montpellier, CNRS, Montpellier, France
[5] Departments of Medical Biophysics and Medical Imaging Western University, London (ON) Canada
[6] Eurostim, Montpellier, France

Corresponding author: Alexandre Legros: alegros@lawsonimaging.ca

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ABSTRACT **Background**: Electric vestibular stimulations (EVS) up to 300 Hz trigger vestibular myogenic responses. Interestingly, 300 Hz is the upper limit of the so called extremely low-frequency magnetic fields (ELF-MF) range found within the 2010 guidelines written by the International Commission for Non-Ionizing Radiation Protection. Such guidelines are used to protect the workers and the public from neurostimulation triggered by induced electric fields. Since EVS is known to bias reaching and pointing tasks, vestibular-specific electric fields at power-line frequency are likely to impact the safety and performance of workers in high ELF-MF environments. **Objectives**: This research aimed to investigate the impact of vestibular-specific electric-fields on manual pointing accuracy. **Methods**: Pointing accuracy of twenty healthy participants was analyzed with both direct current (2 mA) and sinusoidal (peak ± 2 mA at 50 Hz) EVS. Spatial orientation and quantity of movement variables were used to investigate pointing modulations. **Results**: Despite a pre-trial conclusive positive control effect, no significant effects of both direct current and 50 Hz stimulation exposures were found. **Conclusions**: Although high vestibular-specific electric fields were used; no pointing accuracy modulation was found. These results suggest that ELF exposure even at high levels are not able to modulate hand pointing performance in humans. Even though this could be explained by context-specific habituation mechanisms rapidly decreasing EVS impact over time, these results represent useful knowledge for the safety and the performance of workers evolving in high ELF-MF environments.

INDEX TERMS Arm motor control, electric current stimulation, human vestibular system, Power-line frequency.

I. INTRODUCTION

In today’s world, given the generation, distribution, and use of alternating current (AC) at sources found at 50/60 Hz, depending on geographic location, both the public and the workers are subjected to ubiquitous Extremely Low-Frequency Magnetic Fields (ELF-MF < 300 Hz) [1]. According to Faraday’s law of induction, changing magnetic flux density over time induces Electric Fields (E-Fields) and currents within conductors such as the human body. Incidentally, such E-Fields can modulate human neurophysiology [2]–[5].

Because of the proximity of ELF-MF sources in our daily lives and the constant interaction between the induced E-Fields and the human neurophysiology, answering health and safety concerns to protect workers and the public is of paramount importance. In that regard, international 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), review scientific data to establish guidelines and standards enacted at national levels [1], [6], [7].

To date, the most reliable effect of synaptic polarization is the acute perception of phosphenes, on which both ICNIRP and IEEE-ICES base their *in-situ* induced E-Fields thresholds [1], [6], [7]. Phosphenes are flickering visual appearances perceived when exposed to a sufficiently strong ELF-MF [8]. Nowadays, the main hypothesis regarding phosphenes is that they result from membrane potential modulations of graded potential retinal cells, impacting in cascade the continuous release of neurotransmitters to the downstream retinal cells through their ribbon synapse [9]. However, phosphene perception is subjective and both the standards and the guidelines could better profit from an objective outcome measure.

Although anatomically different, the vestibular hair cells share, extensive neurophysiological properties with the retinal photoreceptors. Indeed, both types of cells use graded potential for signal processing [10], both releasing glutamate gradually from ribbon synapses [11]–[14].

Vestibular hair cells are mechanoreceptors found in both the canals and the otoliths (composed of the utricle and the saccule). Their role is to transduce 1) head movement information and 2) the static head orientation relative to the earth's gravitational pull, into electric signals integrated and treated by the central nervous system (CNS) [15].

Compellingly, as for the retinal cells [16], [17], small intensity E-Fields easily activate the vestibular hair cells [18]–[22]. Moreover, increased activity within pigeons' vestibular nuclei is recorded when they are subjected to the induced currents produced by ELF-MF stimulations [23]. Furthermore, recorded voltage modulations within a semicircular canal model [23] also provides evidence for a potential electromagnetic induction impact on the vestibular system [23]. Thus, given their important sensitivity to E-Fields [18]–[22], vestibular hair cells could potentially be predisposed to being modulated by the power-line frequency ELF-MF induced currents and provide objective outcome measures needed for future international guidelines and standards.

Given the important role the vestibular system plays in balance, we investigated the impact of powerline frequency E-fields on postural control in the past [24]–[26]. However, due to potential biomechanical and neurological low pass filtering mechanisms [27]–[29], no postural impact was found. Yet, E-fields at powerline frequencies could be more impactful as the outcome is recorded further up from the feet and closer to head [27]–[29]. Indeed, in humans, sinusoidal vestibular-specific electric stimulations (EVS), modulate neck myogenic responses at frequencies ranging up to 300 Hz [30]. However, to record such modulations, strong isometric neck muscle contractions with the head fixed is needed. This unfortunately does not match daily life or working environments. Furthermore, to obtain neck myogenic results at 300 Hz, electrodes had to be inserted within the muscles under ultrasound guidance which is not convenient for replication studies needed to strongly base the *in-situ* threshold values. Indeed, to protect and safeguard both the public and the workers in their respective environments, the international Standards and guidelines should profit from more easily recorded behavioral outcomes.

Afferent vestibular information is largely used during intentional human motor control tasks. For instance, such sensory information has been illustrated in many pointing or reaching behavioral studies [31]–[34], and such arm movements are also perturbated when EVS is the source of vestibular modulation [35], [36].

This study investigates the impact of vestibular-specific E-fields at power-frequency on arm movement performance during a pointing task. Given that both the retinal photoreceptor and the vestibular hair cells are very similar from a neurophysiological standpoint, this study further investigates an alternative model to the retinal photoreceptors and phosphene perception while appreciating the performance and safety of the employees working in high ELF-MF environments. Given that EVS is known to notably induce myogenic responses above powerline-frequencies [29], [30], we hypothesized it will modulate the pointing task performance by decreasing the performance.

II. MATERIALS AND METHODS

A. PARTICIPANTS

Twenty (20) healthy right-handed participants (10 females-10 males) aged between 19-49 (mean ± SD = 25 ±7) were recruited for the study. All participants were tested within the Euromov-DHM laboratory at the University of Montpellier, France. Written informed consent was obtained from each participant prior to the experiment. The study was conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of the University of Montpellier (IRB # 2001D).

Were excluded volunteers with a history of any vestibular-related pathology or dysfunction, any ophthalmological (including color blindness) and auditory problems, any orthopedic dysfunctions, as well as any chronic illnesses and neurological diseases. We're also excluded participants having permanent metal devices above the neck [37]. Finally, to avoid any interactions influencing the E-Fields, participants had to refrain from exercise, alcohol, caffeine, nicotine, pharmaceutical and/or drug intake 24 hours before the study [38].

B. EXPERIMENTAL DEVICES

To set up the task, we made our own experimental custom-designed table. To maximally standardize the pointing task, the height of the wooden table could be adjusted from 70 to 98,5 cm to level it with the participants' hips. To provide the experimental visual targets, we embedded four LED lights within the wooden structure (Fig. 1). Each LED was 5 mm in diameter and had identical characteristics. All LED targets produced a green light except the reference LED (LED-R) which, in this case, was red (Fig. 1). All green LED targets were distanced 30 cm away from LED-R (Fig. 1). The first target (LED-1) was placed directly in front of the participants, in-line with LED-R. The second target (LED-2) was located at a 45° angle clockwise from LED-1 (Fig. 1). The last target (LED-3) was set to the right of the participant at a 90° angle clockwise from LED-1. Both the LEDs' ignition and extinction were controlled by a custom MATLAB script (MatLab version 9.3 – The MathWorks Inc., USA).

To track the arm movements during the pointing task we used a Liberty motion tracking system (Polhemus Ltd., Colchester, VT, USA). The pointing data was recorded at 240 Hz with the stylus provided with the liberty system. Finally, the liberty's antenna (TX2 model, Polhemus Ltd., Colchester, VT, USA) was set in line with LED-1 at the edge of the experimental table (Fig. 1).

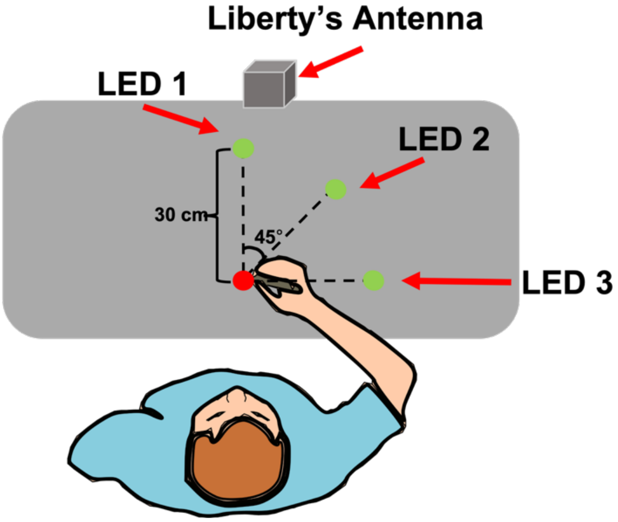

FIGURE 1.
Schematic experimental setup seen from above. All LEDs were embedded in the wooden table. The red dot (LED-R) signifies the starting point. Each green LED indicates the pointing targets to aim at. Each target was distanced 30 cm away from LED-R. LED-1 was set in line with LED-R. Starting with LED-1, LED-2 and LED-3 were consecutively set 45° clockwise.

C. ELECTRIC VESTIBULAR STIMULATIONS

We delivered EVS using a transcranial current stimulation device (StarStim, Neuroelectrics, Spain) driven by the NIC software (Neuroelectrics Instrument Controller, version 1.4.1 Rev.2014-12-01) via Bluetooth. To facilitate signal synchrony and data analysis, the NIC software was piloted by the same custom MATLAB script steering the LEDs.

To provide proper conduction between the electrodes and the skin, we saturated the circular 25 cm2 Ag/AgCl electrodes (StarStim, Neuroelectrics, Spain) with 8 mL of saline solution. We then secured the electrodes using the StarStim exposure cap and tape. To ensure appropriate stimulations, we maintained electrodes' impedances below 10 kΩ through-out the experiment, as recommended by the manufacturer.

We used the same binaural bipolar montage for the Direct (DC - 2 mA), the Alternating (AC - peak ± 2 mA at 50 Hz) electric and the SHAM stimulations. The intensity of the current was chosen with the following rational. Vestibular outcomes start being recorded with 0.1 mA [39] but prickling and burning sensations can be felt above 2 mA [38]. Therefore, we decided not to stimulate above the recommended 2 mA threshold [38]. Here, SHAM is described as a procedure in which the current is ramped up and then turned off at the beginning of the test period that matches the period used with active stimulation. The current is then turned on again at the end of the testing block and ramped down until it is turned off. Each stimulation condition lasted 3.5 min and had the same pattern. The current was initially ramped up over a 15 s period, followed by a 3 min stimulation or SHAM (no current), and ended with an equivalent 15 s ramped down at the end of the condition (Fig. 3). For DC stimulations, we placed the cathode behind the right mastoid process.

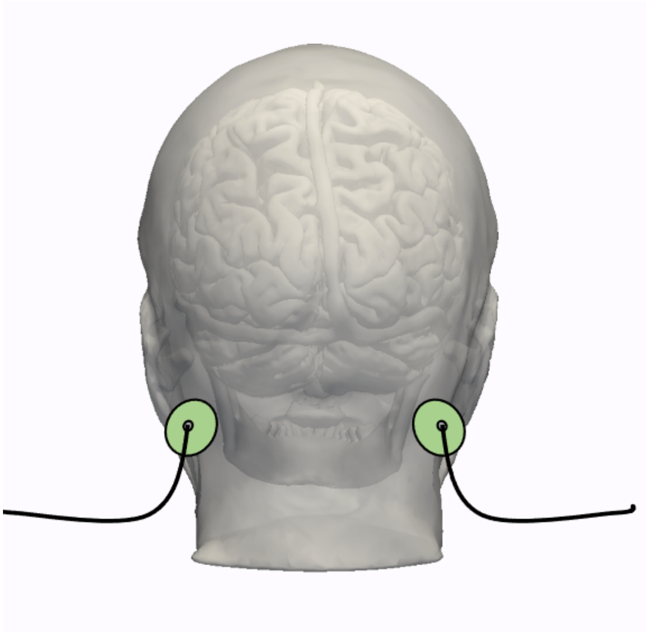

FIGURE 2.
Classical binaural bipolar montage used for the direct and the alternating vestibular stimulations. In both cases the electrodes (green circles) are set at the back on the mastoid processes. For DC stimulations, the cathode is arranged at the back of the right mastoid process and the anode is put at the back of the left mastoid process.

We first ensured our EVS stimulations were efficient before recording the trials. Thus, before starting the testing, we exposed the participants to 10 seconds 2 mA DC trials while standing feet together, arms by their side and eyes closed, and made sure each participant swayed towards the anodal side in the frontal plane (for review [40]).

D. BEHAVIORAL TASK

The study employed a double-blind, repeated-measures design. The experiment was carried out over a single 45 min session. It was divided into 3 runs of 3 randomized blocks (one for each stimulation condition: DC, AC, SHAM) (Fig. 3). Each randomized block lasted 3.5 min. The pointing task started once the current or SHAM had reached its plateau (or no current) and ended before the current was ramped down. During this 3 min block period the participants had to point 30 times to the randomly lit LEDs. Thus, each pointing maneuver lasted 6 seconds. All 3 experimental runs were carried out in a completely darkened room. Only the lighted LEDs provided visual information to offer guidance for spatial orientation.

At the beginning of each trial (pointing action), we asked the participants to set the stylus pen on the red LED-R which was considered as the starting point. After 1.5 seconds the LED-R was switched off, and the participants heard a beep indicating to start pointing. Simultaneously, one of the green LED was randomly turned on during 1 second. To avoid any rhythmic habituation, the participants ended the pointing maneuver by coming back to the lit LED-R once they heard a final beep which was randomly set in time after the green LED was turned off.

Within a given run (Fig. 3), the 3 blocks were performed consecutively, with each block starting 30s after the previous one, This resting period was done to dissipate the stimulation effects and allow the vestibular system to reach its normal resting firing rate between blocks [41]. To avoid fatigue and boredom, the lights were switched back on during 3 min, and the participants could relax and rest between each run (Fig. 3).

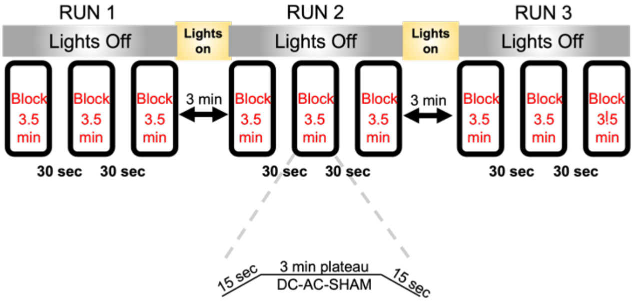

FIGURE 3.
Schematic representation of the protocol. The entire session consists of three distinct runs, each encompassing three 3.5 min randomized blocks done in complete darkness, separated by 30 sec rest periods. During each randomized block, the participants pointed 30 times to a randomly lit LED during a 3 min stimulation period. Between runs, the light was turned back on for 3 min to provide more rest.

E. DATA ANALYSIS

- *Pointing errors*

The arm movement time series were filtered with a low pass bidirectional 4th order Butterworth zero-phase digital filter with a cutoff frequency of 20 Hz. To have a broad view of the pointing errors, we decided to analyze them both quantitatively and qualitatively. The quantitative approach aimed at looking at the amount of error while the qualitative looked more specifically at the spatial distribution. Thus, for the three specific targets, for each type of stimulation (DC, AC, SHAM), we analyzed the pointing errors using five different variables: 1) the global pointing errors, 2) the Antero-Posterior (AP) pointing errors, 3) the Medio-Lateral (ML) pointing errors, 4) the mean direction of the pointing errors and 5) the error variability in space.

First, quantitatively, for the first variable, we processed the global pointing errors as the Euclidean distance between the Cartesian coordinates of the mean pointing score and a given LED (Fig. 4A). Then, for the second and third variables, we computed the pointing errors more specifically as the distance between the mean pointing score and the LED along both the AP and ML axes (Fig. 4A).

Qualitatively, during each trial, the participants targeted one of the enlightened LED 10 times (30 pointing maneuvers for 3 specific LEDs). To analyze the spatial dispersion of these pointing errors around a specific LED, we computed the ellipse encompassing them. The ellipse was computed using a Principal Component Analysis (PCA) method [42]. Two variables were extracted from this analysis.

First, the mean direction (θ) of the pointing errors in space (Fig. 4B). The main direction of the pointing errors is described by the first principal component (PC1) which accounts for the largest part of the variance. θ, the angle between the ML axis and the PC1 axis was computed to describe the main direction of the pointing errors. θ was always presented within 0° and 180°: 0° being aligned with the ML axis (Fig. 4B). Finally, we used the ellipse area as a measure of error variability (Fig. 4C).

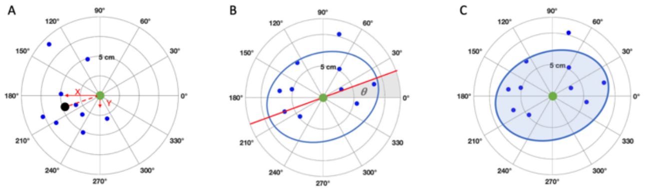

FIGURE 4.

Graphical representation of the pointing errors dependent variables. In all panels, the green dot represents a LED target, and the blue dots embody the pointing coordinates for one trial. A) The black dot symbolizes the mean pointing score. The red dotted line quantitively represents the Euclidean distance describing the Global error which can then be decomposed along both the X and Y axes. B) The red line represents the main direction of the pointing errors in space at an angle θ symbolized by the grey shaded area. C) The blue ellipse is an example of the measure of error variability using the ellipse area (blue shaded zone).

- *Statistical analysis*

A level of significance of α = 0.05 was adopted throughout data analysis. We performed all linear statistical analyses using the open source JASP software (University of Amsterdam, Netherlands, version 0.15). Two-way ANOVAs (3 stimulation modalities (DC/AC/SHAM) × 3 LEDs) for repeated measures were used to test the effect of the stimulation exposure types on the Global, AP and ML pointing errors, as well as for the ellipse area.

For θ analyses, circular statistics were used using the circular library in R. Using Rayleigh's test for spacing test for circular uniformity of the distributions, we first ensured that θ data samples were not distributed uniformly. Mean θ and Angular Deviation (±AD) were used to describe the main direction of sway. A Watson-Williams multi-sample test was used per LED to investigate the effect of the different stimulations on the main error direction.

III. RESULTS

- *Quantitative differences in pointing errors*

Two-way ANOVAs for repeated measure did not provide evidence of interaction effects (LED positioning * Stimulations) for Global (F (4,184) = 0.942; p = 0.441), AP (F (4,184) = 0.872; p = 0.482) and ML (F (4,184) = 0.193; p = 0.942) pointing errors respectively. Likewise, no stimulation main effect was found for Global ((F (2,92) = 0.281; p = 0.756) (Fig. 5), AP (F (2,92) = 2.306. p= 0.106) and ML (F (2,92) = 0.943; p = 0.394) pointing errors. However, a main effect of LED positioning was found for Global ((F (2,92) = 27; 374; p < 0.001) (Fig. 5), AP (F (2,92) = 8.474; p < 0; 001) and ML (F (2,92) = 122.549; p < 0; 001) errors. A first post hoc Holm-Bonferroni procedure [43] showed that an increased global distance error was more likely committed when targeting LED 1 rather than LED 2 (Mean error distance = 0.87cm ± SE = 0.15; t (5.661) p < 0.001) and LED 3 (Mean error distance = 1.07cm ± SE = 0.15; t (6.957) p < 0.001). Furthermore, the same Holm-Bonferroni procedure [43] showed that the errors were more medial in ML and more likely undershot in AP when targeting LED 1 rather than LED 2 (Mean ML error distance ± SE = -2.68 cm ± 0.19: t (-14.03) p < 0.001. Mean AP error distance ± SE = -1.318 cm ± 0.10; t (-3.986) p < 0.001) and LED 3 (Mean ML error distance ± SE = -2.48cm ± 0.33; t (-13.02) p < 0.001, Mean AP error distance ± SE = -0.954 cm ± 0.33; t =-2.884 p = 0.01).

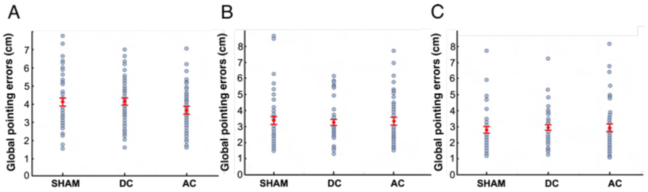

FIGURE 5.

Global pointing errors occurring during the three types of stimulation for the first LED 1 (A), LED 2 (B) and LED 3. Each blue dot represents the value of the Euclidean distance in cm between a LED and a pointing performance. The red diamond embodies the mean global pointing error along with the standard deviation.

- *Qualitative differences in pointing errors*

Fig. 6 depicts results for θ and ellipse areas for each LED and for all three stimulation types (DC, AC, and sham). Two-way ANOVAs (3 stimulation modalities (DC/AC/SHAM) × 3 LEDs) for repeated measures indicated no interaction effects for ellipse area (F (4.176) = 1.201, p = 0.32). Similarly, no significant main effect of stimulation condition was found (F (2.88) = 1.163, p= 0.317). However, once again a main effect of LED positioning was found (F (2.88) = 8.739, p<0.001). Here, a post hoc Holm-Bonferroni procedure showed that an increased area was more likely to happen when targeting LED 2 rather than LED 1 (Mean ± SE = 2,503 cm^2 ± 0.792; t(2) =3.161, p = 0.004) and LED 3 (Mean ± SE =3.128 cm^2 ± 0.792; t(2) =3.050, p < 0.001). Finally, using the three Watson-Williams multi-sample tests (one per LED), no significant differences due to stimulation type were found for θ for LED 1(F(2) = 0.63; p = 0.533), LED 2 (F(2) = 0.45; p = 0.641) and LED 3 (F(2) = 1; 17; p = 0; 312)).

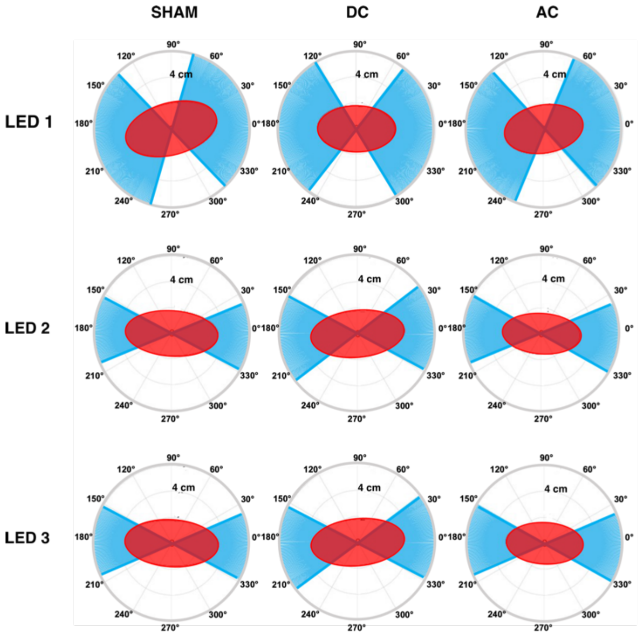

FIGURE 6.
Qualitative representation of the pointing errors in space for all three LEDs and all three stimulations (SHAM, DC, AC). The area of the red ellipses is a representation of the measure of error variability. The red ellipses are oriented along an angle θ, indicating the main direction of the pointing errors.

IV. DISCUSSION

When subjected to both electric and time-varying magnetic fields at powerline frequency, people are susceptible to perceive and report phosphenes. Today, the main hypothesis is that phosphenes result from the membrane potential modulation of the graded potential cells found at the retinal level [5], [9]. Interestingly, the vestibular hair cells are also graded potential cells. Consequently, from the perspective of the guidelines, the investigation of the ELF-MF induced E-fields on the vestibular system was though legitimate for two reasons: 1) to consider an alternative model providing objective outcome measures and 2) appreciate the performance and safety of the employees working in high ELF-MF environments. These goals are in line with international Standards and Guidelines' intended ambitions to fill the knowledge gaps [44] needed to answer the health and safety concerns to protect the workers and the public alike while in ELF-MF environments [7].

Given the very important neurophysiological similarities between the retinal and the vestibular sensory cells [45]–[47] and the fact that EVS above power-line frequencies triggers myogenic responses [29], [30], this study aimed to investigate the impact of EVS at 50 Hz on a human pointing task. As E-Fields and currents trigger the vestibular hair cells [18]–[20], [22] and vestibular signals affect reaching movements [48], [49], we hypothesized that EVS would decrease the arm motor control performance.

Only a main effect related to LED positioning was found in our study. Given that no other effect was recorded, we can only understand this has resulting from biomechanical constraints. Although we tried to standardize the participants' position relative to the table by adjusting the table's height at the hips, the target positions were fixed. As the target positions were not adjusted to the participant's arm length for instance [33], this could have resulted by biomechanically restraining participants when pointing at specific targets.

Prior to the pointing task, to make sure our electric stimulations were appropriately applied and strong enough to induce behavioral effects, we used the same 2 mA DC stimulation on all subjects while they were standing eyes closed and feet together. As predicted, our 2 mA DC stimulation destabilized all participants towards the anodal side in the frontal plane (for review see[40]). Therefore, in this study, before the pointing task, DC was used as a positive control which is defined, herein, as a condition in which specific known effects are expected [50].
However, contrary to our hypothesis, our findings showed no increased pointing errors neither with DC nor AC stimulations. A first explanation for our results could be that the 2-mA intensity was too low to directly impact the pointing maneuvers. Indeed, some studies demonstrated arm motor control modulation using 2.5 mA [36], 3 mA [49] and up to 4 mA [35]. Nevertheless, this is surely unlikely. First, in all the aforementioned studies, the participants were stabilized either by being seated [35], [36], or by using a bite-board to prevent possible EVS-induced head motions [49]. To obtain more important vestibular outcomes, greater stimulation intensities are needed with increased body stabilization [40]. In our study, to try to be as close to an ecological working environment as possible, our participants stood unstabilized while pointing. Second, EVS outcomes have been recorded at intensity much lower than our 2mA stimulations. Vestibulo-ocular outcomes for instance are triggered only with 0.1 mA [39] and the threshold modulating postural control was found at 0.32 mA [51]. Thus, our 2-mA stimulation was expected to trigger responses.
One could argue that compared to DC, the sinusoidal aspect of AC helped in lowering the intensity of this stimulation. However, this is also improbable as the intensity of transcranial electric stimulations does not reduce up to 1000 Hz [52]. Therefore, given that both our DC and AC stimulations were over 6-fold higher than the reported 0.32 mA postural threshold [51] and 20 times higher than the 0.1 mA threshold triggering vestibulo-ocular responses [39], both stimulations were strong enough to impact the vestibular system.

EVS-induced vestibular responses follow a craniocentric rule. When the head is facing forward the responses are found in the frontal plane toward the anodal side [40]. Yet, as the head is turned, the orientation of EVS motor outcomes change accordingly by a similar magnitude [53], [54]. Fitzpatrick and Day provided a model in 2004 [40], revised in 2011 [55], explaining that the EVS response is mainly explained by summing the six canalithic vectors around which head rotations are perceived. This gives rise to a resultant vector around which the EVS-induced rotation occurs. This resultant vector is oriented backwards in the sagittal plane with an upward component of approximately 18 degrees from Reid's stereotactic plane (the plane joining the ear to the lateral border of the eye) [40]. This explains why the outcomes given by EVS stimulations produce mainly canalithic outcomes [56] with a roll component. In the present study, because workers are not limited in their head movements during their shift, we did not control participant's head orientation. Undeniably, this could have modulated responses in the frontal plane [57], [58]. Such changes could be implemented in future protocols. Nonetheless, this would not reflect real-life performance nor give rise to information related to their safety.

Reaching outcomes changes due to vestibular modulation have been hypothesized as either the result of an altered egocentric target location or a neural mechanism stabilizing the arm in space [34]. EVS impacts cognitive functions in relations to space [33], [59]–[65]. Indeed, the vestibular system is highly implicated in spatial orientation [59] as it plays an important role in space perception [66]–[69] and distance estimation [70]. EVS also alters the knowledge of arm position in space [35], [71]. Therefore, greater pointing errors could have been expected with both DC and AC EVS stimulations.

Besides the vestibular system, pointing to a target, requires the use of other senses such as vision and proprioception. Moreover, the integration of vestibular afferences is multisensory in nature [72]. EVS modulate proprioception integration [73]–[76] which could also have been a factor of increased pointing errors.

Regarding vision, our study was carried out in a completely darkened room. Nonetheless, the participants saw the enlightened LED to point at. Therefore, this visual feedback could have helped in modulating the arm trajectory online to compensate for the ongoing EVS effect. Thus, potential greater effects could have been analyzed if the protocol implemented targeting a memorized visual target in the dark. Nonetheless, although workers may work in dark environment such as during the night, or in unlit spaces, they never work blindfolded, nor eyes closed. Thus, modifying our protocol in this sense would have had very little carry over for real life expectations. Furthermore, although it is commonly thought that EVS outcomes decrease when visual input is available, studies show that closing the eyes does not reduce nor abolish responses [77], [78].

Moreover, other eye-hand coordination tasks necessitating both eyes open and good proprioceptive feedback are influenced by EVS. For instance EVS, with only a 1mA intensity, biases the line bisection task in healthy participants [73]. The line bisection task is a widely used test to evaluate spatial cognition [79]. During this test, participants draw a vertical line, aligned with their trunk midline, indicating the middle of a horizontal segment. Thus, as in our pointing task, both vision and proprioception are also used during the line bisection task.

Interestingly, the line bisection biases were obtained with a much shorter stimulation time. Indeed only a 8-second timeframe was needed to trigger errors [73]. In contrast, in our study, to try, once again, to analyze how E-Fields could impact workers in their work environment, we chose the much longer period of 3 minutes. During standing protocols, EVS-related responses are rapidly attenuated and vestibular outcomes saturate within the first 40 seconds of stimulation [80]. During that 40 seconds period, an 18% decrease in vestibular gain also occur as rapidly as 19 seconds while standing [81]. In our study, to compare the DC, AC, and SHAM conditions, we analyzed the pointing errors during the 3-minute plateau during which the participants had to point 30 times to the randomly lit LEDs. Yet, given this 3-min stimulation period, a 15 second ramp gradually increasing the intensity was imposed by the NIC software for participants' comfort. Intensities as low as 0.1 mA start triggering vestibulo-ocular responses [39]. Therefore, by the time the stimulations' intensity reach the 2-mA peak after the 15 second ramp, the vestibular gain loss could already have reached an 18 % decrease. Although. the first couple of pointing maneuvers could have been impacted by the stimulations, given that each pointing maneuver started every 6 seconds, the average error could have been dampened over time with increased stimulation's habituation. Furthermore, EVS-induced habituation seems to importantly depend on task-dependent mechanisms [81] which could, in our context, be even greater. Indeed, to our knowledge, no specific study as looked specifically at the EVS-habituation mechanisms in pointing tasks.

V. CONCLUSION

The intensity used herein was 2-mA. This likely translates to 0.16 V/m peak at the canalithic system [82]. Such value is much higher than the 0.075 V/m peak synaptic modulation threshold used in the international guidelines for the ELF-MF range [7]. Yet, although only 0.1mA (0.008 V/m) impacts the vestibular system [39] we did not record specific behavioral modulation during the pointing task in our study. Nonetheless, 2-mA EVS above powerline frequency impacts the vestibular system [29], [30]. Therefore, until proven otherwise, from a Standards/Guideline's perspective, this argues against potential powerline ELF-MF adverse effects at this E-Fields levels.

Nonetheless, further studies will have to concentrate on potential mid- and long-term health-related issues. Altogether, our results could be due to habituation mechanisms decreasing the EVS impact explaining why this modulation did not translate behaviorally through the chosen pointed task. Thus, from both performance and safety perspectives, workers should particularly pay close attention to security procedures when first emersed in ELF-MF environment and wait a couple of minutes for the habituation process to take place to ensure optimal safety and performance during their work shift. Finally, to date, phosphene should remain the main model on which both the international guidelines and Standards should be based.

ETHICAL STANDARD

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of Euromov-DHM laboratory at the University of Montpellier, France (IRB # 2001D approved on October 7th, 2020).

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NICOLAS BOUISSET received the B.A.Sc. degree in sport science from the Université de la Réunion, France, in 1999, and the physiotherapy degree from the Université Catholique de Louvain-la-Neuve, Belgium, in 2003. After working clinically for over a decade, he received the M.S. degree in human movement science from the Université de Montpellier, France, in 2015 and his Ph.D. in kinesiology in 2020 from the University of Western Ontario, Canada. His current research interests include vestibular function modulations using both Galvanic Vestibular Stimulations and Extremely Low Frequency Magnetic Fields.

ANDRES CARVALLO received the engineer in telecommunications degree specialized in signal, imaging, embedded systems, and automatic control from the University of IMT Atlantique, France in 2013 and his PhD degree in biomedical signal processing from the University of Rennes 1, France in 2018. He has been working as a researcher in the University of Montpellier since 2020. His research interests include exposure limits to extremely low frequency electric and magnetic fields, human experimentation, and dosimetry studies.

PERRINE DUMUR

SOFIANE RAMDANI is currently an associate professor at the University of Montpellier, France. He received an engineering degree in signal processing in 1995. The same year, he obtained a Master's degree in image processing from the University of Toulon, France. He received his PhD from the same university in 1999, studying specific nonlinear and chaotic dynamical systems. His main research interests are in the area of nonlinear time series analysis techniques, with applications to neurophysiological signals and human movement data.

Dr. ALEXANDRE LEGROS is Director of the Bioelectromagnetics and Human Threshold Research Group at the Lawson Health Research Institute; Associate Professor with the Departments of Medical Biophysics, Medical Imaging, and Kinesiology of Western University in London ON, Canada; and a scientist at EuroMov-DHM, University of Montpellier, France, where he is duplicating his Canadian laboratory and developing new collaborative research projects involving human nervous system responses to electric and magnetic stimulations.

Dr. Legros received the Ph.D. degree in human movement sciences in 2004 from the University of Montpellier. He completed a first postdoctoral fellowship on electrical deep brain stimulation (DBS) in patients suffering from dystonic syndromes (Neurosurgery unit of Guy de Chauliac Hospital, Montpellier, France), and a second postdoctoral fellowship in the Bioelectromagnetics Group of the Lawson Health Research Institute (London ON Canada), where he is a Scientist since 2007. He has expertise in the fields of neurosciences, kinesiology, and biophysics applied to the study of neurostimulation and neuromodulation. His research interests mainly relate to the effects of specific electric and magnetic stimuli (DBS, transcranial magnetic stimulation, and time-varying magnetic fields) on human brain processing, motor control, and cognitive functions. He was a Board Member and then secretary of the BEMS society (from 2013 to 2020). He organized the BioEM2019 international conference in Montpellier, France. He is currently Canadian chair for URSI commission K, co-chair of the subcommittees 3 and 4 within the IEEE-ICES TC95, and chair or the Editorial Working Group in charge of the next Standards revisions in the Low Frequencies. He is also co-chairing the Non-Ionizing Radiations Task Group of IRPA with Dr. Julien Modolo (International Radio Protection Association).