

Experimental und environmental factors influencing human perception of direct current-, alternating current-, and hybrid electric fields

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Identification of Environmental and Experimental Factors Influencing Human Perception of DC and AC Electric Fields

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As part of the energy transition in Germany, high-voltage direct current (HVDC) lines producing DC electric fields (EF) are in planning. Since the human perception of DC EF was rarely investigated in the past, we aimed to identify environmental and experimental factors influencing the human perception of direct current (DC) EF, alternating current (AC) EF, and the co-exposure of DC EF and AC EF (hybrid EF) under whole-body exposure. Additionally, first estimates of DC EF and AC EF perception thresholds as well as differences in human perception of DC EF and AC EF concerning the type of sensation experienced and the affected body part were evaluated. A highly sophisticated exposure lab was built to expose participants to various EF strengths and ask for their assessment concerning the presence of an EF. To estimate the individual perception thresholds of 11 participants, the signal detection theory as well as the single-interval-adjustment matrix procedure were applied. Relative humidity could be identified as an environmental factor influencing the perception of AC EF and DC EF in different ways. An appropriate ramp slope and an exposure duration for future studies could be elaborated. Additionally, perception thresholds were lower under hybrid EF exposure than under DC EF or AC EF exposure alone. Cutaneous sensations evoked under DC EF and AC EF exposure were individually different and attributed to various parts of the body. Several environmental and experimental factors influencing the human perception of EF could be identified and provide an essential basis for a large-scale study.-*Bioelectromagnetics*. 2021;42:341–356. © 2021 Bioelectromagnetics Society.

Keywords: electric field; exposure; high-voltage power line; psychophysics; signal detection theory

INTRODUCTION

In recent years, the use of various energy sources has been extensively discussed, remarkably increasing the importance of renewable energies, such as wind energy, solar energy, or hydropower on a global scale. However, locations where energy is harvested are often far apart from those where it is needed. Consequently, new and efficient transmission lines are becoming more and more necessary. For transporting electric energy over long distances, high-voltage direct current (HVDC) interconnections show many advantages over the broadly distributed high-voltage alternating current (HVAC) lines. Therefore, HVDC lines have been built in several countries, such as Canada, the United States, China, and Sweden, and are

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currently in planning in many other countries. In Germany, for example, HVDC transmission lines will be used to transfer energy from offshore windfarms in northern Germany to western and southern metropolitan and industrial areas.

Overhead HVAC transmission lines constantly produce alternating electric fields (EF) of varying intensities. The highest EF strengths at ground level can be measured at the midpoint between two pylons, where transmission lines come closest to the ground [ECOLOG, 2010]. With increasing distance to the power lines, EF strengths decrease rapidly [ECOLOG, 2010]. According to the International Commission on Non-Ionizing Radiation Protection (ICNIRP), EF strengths at ground level must not exceed the value of 5 kV/m (rms value) for 50 Hz fields [ICNIRP, 2010]. For DC EF, no limit values for human exposure were published by the ICNIRP [ICNIRP, 1998] as DC EF do not enter the human body and have therefore no direct health effects. Within areas of HV power line right-of-way (or similarly defined areas, e.g., easement or corridor), the International Committee on Electromagnetic Safety (ICES), as part of the Institute of Electrical and Electronics Engineers (IEEE), recommends a maximum value of 10 kV/m to prevent spark discharges when a person touches a conductive path to the ground [IEEE, 2019]. The EF around the conductors can produce electrical discharges accompanied by the ionization of the surrounding air molecules and the release of trace amounts of ozone and nitric oxide (corona discharges). On HVDC lines, the area of charged ions generated by corona discharges around the transmission lines is larger than that on HVAC lines [Blondin et al., 1996]. In some cases, HVDC lines will also be mounted on already-existing HVAC pylons, which leads to the coexistence of DC EF and AC EF referring to hybrid EF. Although many HVDC lines were built years ago, human perception of DC EF and hybrid EF was rarely investigated in the past.

According to the World Health Organization [WHO, 2006] and a systematic review covering biological effects of DC exposure in humans and vertebrates [Petri et al., 2017], there are no chronic health effects caused by DC EF. HVDC transmission lines cannot induce currents in conducting objects, in contrast to HVAC transmission lines. Nevertheless, charges on the body surface of an object can be accumulated and perceived by humans even if no specific receptors have been detected yet [Blondin et al., 1996]. Within a couple of studies, the perception of local EF by exposing different parts of the body, such as the participant's forearm, was investigated. Human participants were able to detect local AC EF between 8 and 33 kV/m [Chapman et al., 2005] as well as local

DC EF at approximately 375 kV/m [Odagiri-Shimizu and Shimizu, 1999]. Under in situ whole-body exposures, participants could averagely perceive EF strengths of about 15 kV/m AC and 25 kV/m DC [Clairmont et al., 1989]. Blondin et al. [1996] used an exposure setup [Nguyen and Maruvada, 1994] to expose 48 participants to uniform DC EF of up to 50 kV/m and ion current densities of up to 120 nA/m² generated by four high-voltage electrodes located in the ceiling of the room [Blondin et al., 1996]. Participants sat in the middle of the room and performed several trials, which were subdivided into four consecutive periods. After increasing the EF from zero to the targeted EF strength using a constant slope of 7 kV/m/s (7 s onset period), the EF strength was maintained for 7 s (observation period). Subsequently, participants had 4 s to answer the question if they could perceive an EF (response period) before the EF strength decreased over 7 s (offset period). In this way, the authors specified the first detection thresholds of 45.1 kV/m for DC EF under whole-body exposure and controlled conditions, which were defined as EF strengths that are just strong enough to be detected correctly by human participants. The presence of air ions led to a decreased DC detection threshold of 36.9 kV/m. Under DC EF exposure, various cutaneous sensations, such as tingling or itching, were described and mostly attributed to participant's hair and parts of their scalp [Blondin et al., 1996]. In contrast, in AC EF body hair tended to vibrate more [Odagiri-Shimizu and Shimizu, 1999; Chapman et al., 2005] and might elicit sensations, such as "wind blows" on the skin [Kato et al., 1989]. In light of the large interindividual variations, Blondin et al. [1996] suggested further investigations of individual characteristics and environmental factors influencing the perception of EF. The coexistence of DC and AC EF, referring to hybrid EF, seemed to cause decreases in detection thresholds compared to separated DC or AC EF [Clairmont et al., 1989]. Under limb exposure, the perception of both local DC EF [Odagiri-Shimizu and Shimizu, 1999] and local AC EF [Kato et al., 1989] was affected by relative humidity. Yet, there is no study considering the influence of relative humidity on human detection of EF under whole-body exposure.

Within the current study, we aimed to determine the most important predictors of human perception thresholds for DC EF, AC EF, and hybrid EF under whole-body EF exposure and highly controlled conditions. It represents a pre-study to identify essential settings for a future

comprehensive main study. We investigated how human perception is influenced by different experimental factors, such as the ramp slope during the increasing period (i.e., the time period until full EF strength is reached), the exposure duration as well as the presence of air ions, and by relative humidity as an environmental factor. Furthermore, we evaluated differences in human perception of DC EF and AC EF in terms of the type of sensation and affected body part.

MATERIALS AND METHODS

Participants

Eleven healthy participants (9 men and 2 women) between the ages of 23 and 33 (mean: 25.45, SD: 3.17) were included in this pre-study, whereby two participants dropped out during the period of the experiments (one participant moved; one started a full-time job). Exclusion criteria were self-reported electrosensitivity, persons fitted with electronic implants or indelible piercings, pregnant women, and persons suffering from skin diseases as well as neurological and psychiatric disorders, such as claustrophobia. Prior to inclusion, every participant

underwent a careful anamnesis followed by a physical examination to assess medication, drug or alcohol abuse as well as cardiovascular, cutaneous, somato-sensory, or mental abnormalities as well as signs of infection.

The recruitment was carried out on the RWTH Aachen University campus and the study was conducted at the University Hospital RWTH Aachen. All participants were briefed about the risks and benefits of the study and gave their written informed consent. All participants obtained an expense allowance of 100 Euro per test day. The study was approved by the ethics committee of the Medical Faculty of RWTH Aachen (EK320/15) and conducted according to the Declaration of Helsinki.

Exposure Lab

For this research project, a laboratory was designed and built at the University Hospital RWTH Aachen in cooperation with the Institute for High Voltage Equipment and Grids, Digitalization and Power Economics, RWTH Aachen University. The construction of the laboratory was based on the experimental setting of Blondin et al. [1996]. The facility (see Fig. 1) included

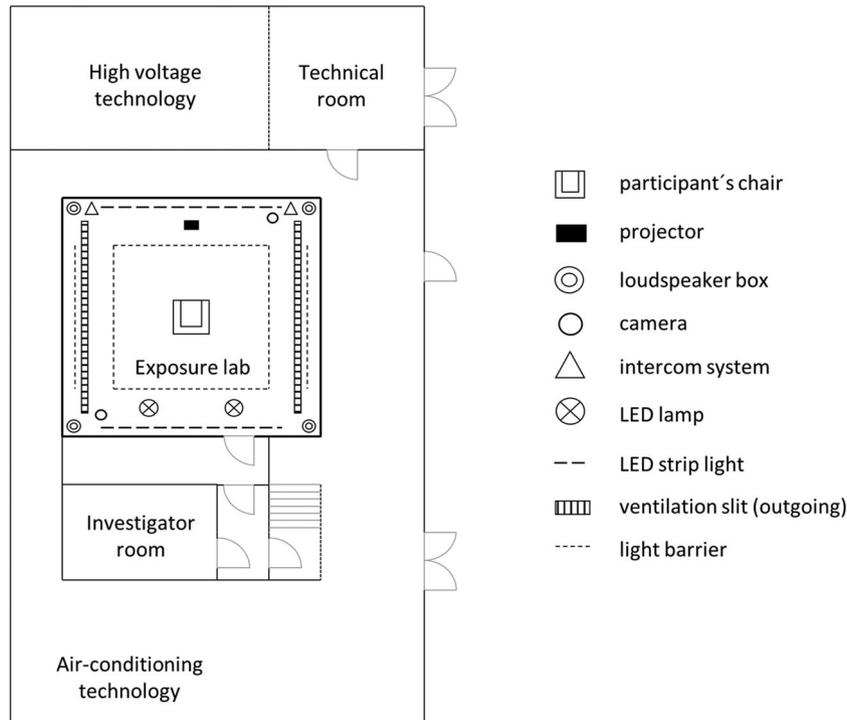


Fig. 1. Schematic top view of the laboratory. The high-voltage equipment with an enclosed technical room was located in the rear area. In the front area, the air-conditioning technology was installed. The exposure lab and the investigator room nearby were located in the middle of the construction. The participant's chair and all technical components were installed inside the exposure lab.



Fig. 2. The exposure lab. The participant's chair was installed in the middle of the exposure lab surrounded by light barriers implemented in the floor. Grading electrodes were mounted on the walls (photo made by Martin Braun Fotografie).

an exposure lab for the participants, a room for the investigator, and a technical room for the lab technician. The exposure lab (see Fig. 2) was 4 m long and wide and three meters high, and contained a central height-adjustable chair. The room and the chair were built of laminated densified wood to prevent conductive processes and charge accumulation. Relative humidity could be set to 30%, 50%, or 70%, whereas temperature was constantly kept at 22 °C (± 0.2 °C). Both relative humidity and temperature were permanently monitored by the duct sensor QFM3160 combined with the measuring tip AQF3150 (Siemens, Zug, Switzerland) and the probe Pt100 (Omega, Deckenpfronn, Germany), respectively. Moreover, air particles that could lead to increased air conductivity were filtered out by an air filtration system. Air over pressure in the exposure lab served to avoid the intrusion of particles from the adjacent room.

Several measures were taken to guarantee real sham exposure conditions and the double-blind study design. Since corona discharges, used to generate ion currents, produce ozone in the air, the amount of accumulated ozone was permanently monitored to exclude ozone as an olfactory confounder. The measurements were executed by the Model 106-L Ozone Monitor (2B Technologies, Kloten, Switzerland) based on UV absorption. Additionally, to exclude perceptions of potential vibrations, e.g., caused by the EF-generating exposure setup or other engines in the same building as a further confounder, the fundament of the exposure facility was placed on a sylomer layer. In order to prevent any acoustic cues, a

65.8 dB(A) incoherent white noise, controlled by an STA-1508 amplifier (Monacor International, Bremen, Germany), was applied in the exposure lab via four BG 20 speakers (Visaton, Haan, Germany) during the experimental task. Additionally, the double-wall construction served as sound insulation against external influences. Participants were monitored live for safety reasons via two cameras, one in front of the participant and one behind (see Fig. 1). An intercom system enabled direct communication between the participant and the investigator. The exposure/sham exposure sequence as well as the EF strengths were applied in an automated and random order. Both the participant as well as the investigator were blinded to the sequence, EF strength, and ion current density. Thus, a directed influence on participant's decisions by the investigator could be excluded. Instructions were projected on the wall in front of the participant (see signal detection theory [SDT] and single-interval-adjustment matrix [SIAM] procedure). Induced body currents due to the EF were tapped by Red Dot 2560 monitoring electrodes (3M, Saint Paul, MN) on both ankles. These monitoring electrodes provided a low resistive connection between participants and the ground so that participant's grounding was ensured during the exposure. To reduce eye fatigue, LED strip lights were dimmed during the experimental task and LED lamps at the back of the participant were switched on.

Several security measures were taken to prevent arc discharge and to ensure participant's safety. First, light barriers in front, behind, at both sides, and above

the participant's head ensured an appropriate safety distance between the participant and the electrodes. An interruption of any light barrier immediately grounded voltage at any time of the experiment within 180 ms regardless of the currently presented EF strength. Second, participants wore a seatbelt with contact plugs at its ends so that standing up led to an immediate shutdown. Third, participants as well as the investigator and the lab technician could actively stop the experiment by pressing an emergency stop. All technical components, such as loudspeakers, cameras, projector, the intercom system, and security measures, were implemented on the raised floor to ensure undisturbed EF conditions in the exposure lab.

High-Voltage System

The EF and ion current generating system were located in the ceiling of the exposure lab and consisted of four high-voltage electrodes. The electrodes were 4 m in diameter and mounted on top of each other (see Fig. 3). Electrodes 1, 2, and 4 consisted of 2 mm-thick perforated aluminum sheets, while Electrode 3 was constructed of single high-grade steel wires with a diameter of 200 μm

and a distance of 0.1 m to each other. Whereas Electrodes 2, 3, and 4 were used to generate a uniform ion current flow, Electrode 1 was primarily used for EF generation. Fourteen grading electrodes positioned on top of each other on the exposure lab walls ensured a homogeneous EF between Electrode 1 and the floor, which was used as the base plate. These grading electrodes were connected via ohmic-capacitive grading units to each other and to Electrode 1. Two-D static EF simulations using COMSOL Multiphysics 5.5 (Comsol, Stockholm, Sweden) were performed to dimension the grading units consisting of the parallel connection of a resistor and a capacitor. Combining a resistance of $R = 5 \text{ M}\Omega$ with a capacity of $C = 20 \text{ nF}$ led to the highest degree of EF uniformity in the vertical direction in the center of the exposure lab, as deviation was smaller than 1% ($|f_{\text{DC,center}}| < 0.2\%$ and $|f_{\text{AC,center}}| < 1.0\%$) (see Fig. 4). In the exposure lab, DC EF strengths with a maximum of 50 kV/m could be generated and combined with ion current densities of up to 550 nA/m². AC EF at a frequency of 50 Hz could reach EF strengths of up to 30 kV/m (rms value). The co-exposure of both field types (AC EF and

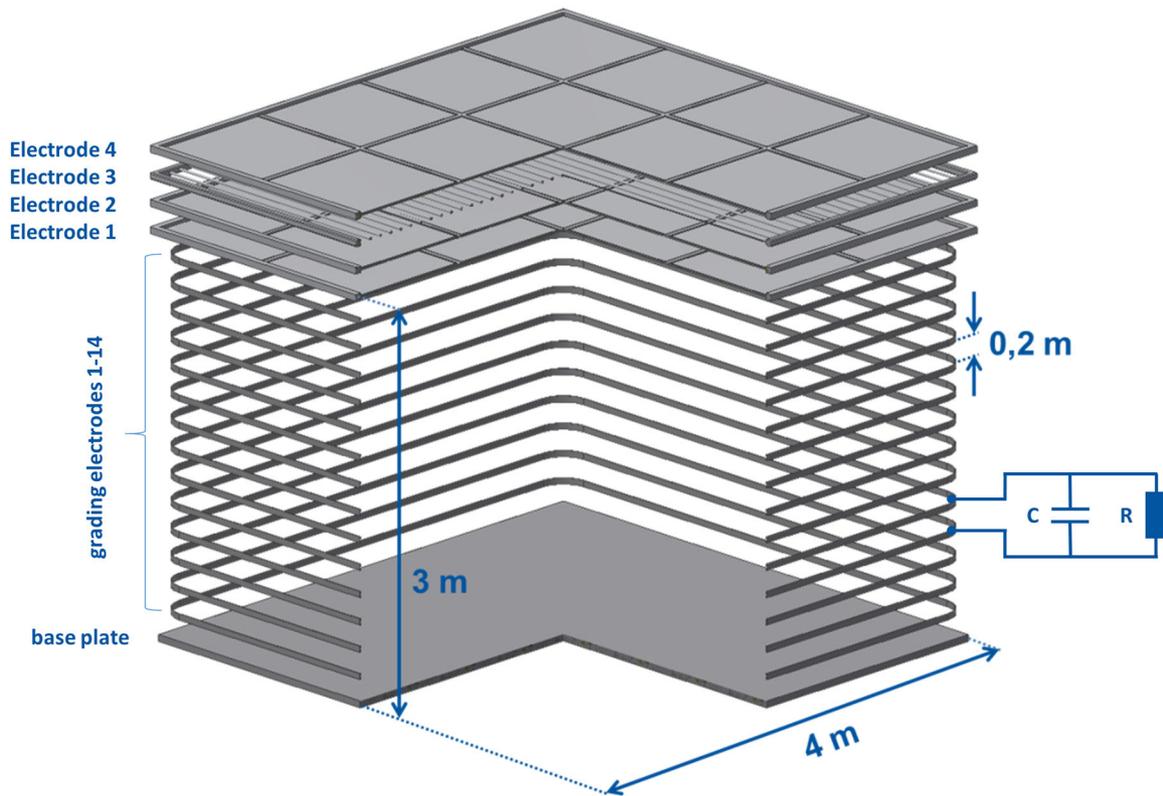


Fig. 3. Electrode arrangement. Four high-voltage electrodes were mounted on top of each other in the ceiling of the exposure lab. Fourteen grading electrodes on the walls ensured a homogenous EF from Electrode 1 to the base plate. EF = electric field.

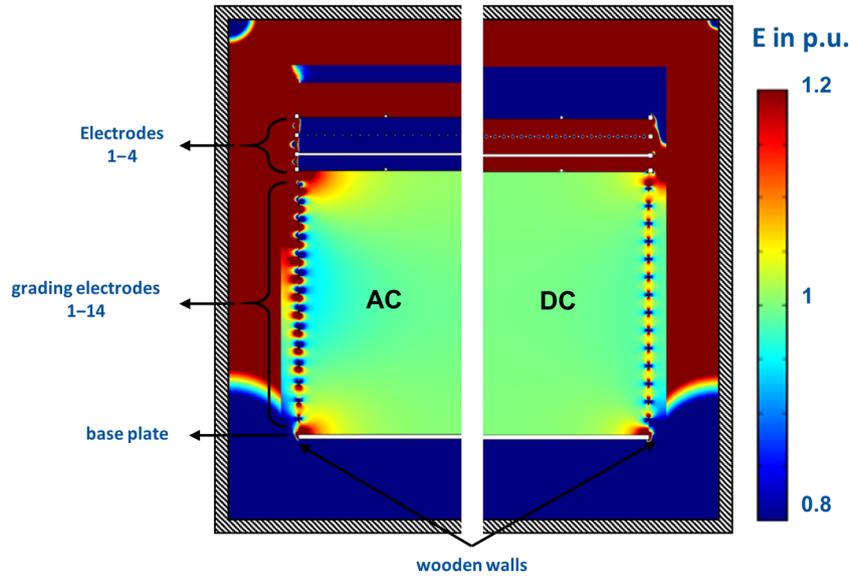


Fig. 4. 2D static EF simulation. 2D static EF simulations using COMSOL Multiphysics 5.5 (Comsol, Stockholm, Sweden) with ohmic-capacitive grading units of $R_{inter}=5\text{ M}\Omega$ connected in parallel to $C_{inter}=20\text{ nF}$ revealed the highest degree of uniformity in the vertical direction in the center of the exposure lab. Apart from the grading units, further components were taken into account, like geometrics and material data. This cross-section through the center of the exposure lab shows the results of an AC EF (50 Hz) on the left side and the results of a DC EF on the right side. The EF strength E and therefore displayed per unit (p.u.). This figure combines the simulation of two exposure conditions. In practice, either AC EF, DC EF, or hybrid EF was present in the entire exposure lab. 2D=two dimensional; AC=alternating current; DC=direct current; EF=electric field.

DC EF, as a hybrid condition in the following) did not exceed EF strengths of 50 kV/m. The lab technician monitored the correct functioning of the high-voltage generation system. To ensure com-

parable and uniform test situations, the height-adjustable chair in the exposure lab was enabled to set the participant's head always to the same level, regardless of the individual body height.

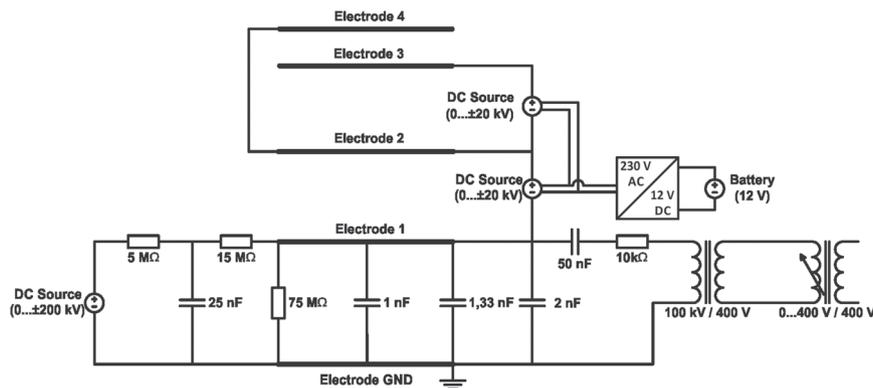


Fig. 5. Circuit diagram. Three independent DC sources and one AC transformer were installed. Electrode 1 was connected to the 200 kV DC source combined with the 100 kV transformer via filter networks. Electrodes 2 and 4 were both connected to the same 20 kV source, while Electrode 3 was energized by another 20 kV DC source. Both 20 kV DC sources were supplied via an insulated 12 V battery. The resistors and capacitors, connecting Electrode 1 to the ground electrode, are representing the resulting value of the grading units and the stray elements of the wooden walls. AC=alternating current; DC=direct current.

Energy for the EF and ion current generating system was provided by three independent DC sources and one AC transformer (see Fig. 5). The EF generating Electrode 1 was energized by a 200 kV DC source in combination with the 100 kV AC transformer. Electrodes 2 and 4 were both connected to the same 20 kV DC source, while Electrode 3 was supplied by another 20 kV DC source. Using independent sources allowed for the controlled generation of various EF combinations. AC EF or DC EF without ion current densities were generated by energizing only Electrode 1. Applying a superposition of DC and AC voltage at Electrode 1 led to the generation of the hybrid condition in the exposure lab. The combination of DC EF with ion current densities was achieved by supplying all electrodes with the same polarity. When applying a voltage between the thin wires of Electrode 3 and Electrodes 2 and 4, corona discharges were generated at the wire surface, resulting in the generation of ions. Depending on the polarity, either positive or negative ions were generated, which moved both ways along the EF lines in equal shares: upwards to Electrode 4 and downwards to the base plate. Some of the downward ions were captured by Electrodes 2 and 1. However, the other ions passed both electrodes and moved to the base plate. The intensity of corona discharges could be adjusted by the voltage difference from Electrode 3 to Electrodes 2 and 4. The voltage between Electrode 1 and Electrode 2 mainly influenced the net rate of ions flowing to the base plate. The described electrode arrangement and the use of independent sources ensured a controlled generation of various EF combined with ion current densities in the exposure lab.

Several calibration measurements were performed to assure compliance between the generated EF strengths and the EF strengths set. For these measurements, the participant's chair was removed from the exposure lab. DC EF with and without ion current were measured by a field-mill type EF probe, while ion current densities were measured via Wilson plate type current density probes. AC EF was determined via the measured displacement current. For all field probes, current amplifiers of the type DLPCA-200 (FEMTO, Berlin, Germany) were installed. Moreover, probes were positioned in a plane with the floor to eliminate possible EF distortions caused by the probes themselves. The uniformity of the EF and ion current density was checked by measuring the EF strength and ion current density at five defined measurement points (see Fig. 6). Required AC EF uniformity was achieved (see Table 1). Quantified variations of DC EF strengths and ion current densities were similar to those measured in the exposure room used by Blondin

[Nguyen and Maruvada, 1994] (see Table 2). Additional calibration and check-up measurements were performed before experimental tasks and controlled at regular intervals. The EF could not be measured during experimental tasks, as the dielectric conductivity of the participant's body would have resulted in field distortions. Nevertheless, the voltage amplitudes generated by the four high-voltage sources were permanently recorded. Based on the data achieved from the calibration measurements, the present EF strength and ion current density in the exposure lab were recalculated at any time and thereby verified. Environmental influences were taken into account by calibration measurements at low and high humidity conditions.

Subjective Procedures

The potential contribution of individual characteristics to EF perception was assessed by a questionnaire. Participants were asked to choose the most accurate type of sensation perceived during exposure (like tingling, itching, vibration) and the affected body part (such as scalp hair, arms, face). Questionnaires were completed separately for DC EF and AC EF immediately after respective exposure sessions.

Psychophysical Methods

Two methods were used to estimate participant's perception thresholds of EF exposure. The staircase procedure (cf. SIAM) is an adaptive algorithm whereas procedures derived from the signal detection theory (cf. SDT) are predefined and therefore readily calculable.

SIAM

The SIAM procedure was originally introduced by Kaernbach [1990] as an unbiased method to determine perception thresholds [Leek, 2001]. It employs an adaptive staircase approach and is based on a random presentation of 50% exposure trials and 50% sham exposure trials. During exposure trials, various DC or AC EF were presented, whereas in sham exposure trials, neither DC nor AC EF were presented. Participants were asked to judge the presence of an EF via a simple yes-no task. Depending on the type of trial, different outcomes were possible: hit, miss, false alarm, or correct rejection (see Table 3). The initial EF strength was set to 20 kV/m for DC EF and 14 kV/m for AC EF. In hybrid sessions, the initial EF strength combination was 20 kV/m DC and 4 kV/m AC. If the EF exposure was detected correctly (hit), the EF was decreased by 4 kV/m on the next exposure trial. An exposure trial eliciting the response "not perceived" (miss) entailed a 4 kV/m increase in the EF. If sham exposure trials were declared as "perceived" (false alarm), the EF was increased by 8 kV/m

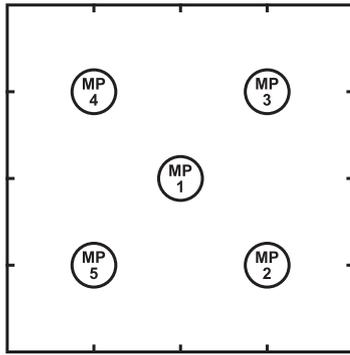


Fig. 6. Measurement points. Five measurement points (MP), equally distributed in the exposure lab, were used to check the degree of EF and ion current density uniformity. During calibration measurements, the participant's chair was removed from the exposure lab. EF = electric field.

(2 × 4 kV/m). Sham exposure trials classified as “not perceived” (correct rejection) had no influence on changes in EF strength. Trials leading to a change of direction in the variation of EF intensity were called reversals [Kaernbach, 1990]. After five reversals, the step size was reduced to 2 kV/m. The SIAM procedure continued until a total of eight reversals were completed. AC EF strengths varied from 6 to 30 kV/m, while DC EF strengths ranged between 16 and 40 kV/m. Due to technical problems, the maximum DC EF strength presented to six participants was 30 kV/m. During hybrid sessions, AC EF was set to 4 kV/m, while DC EF varied from 6 to 30 kV/m.

SDT

A well-established method to estimate a person's sensitivity toward a given signal is provided by the SDT, which originates from the scientific work of

Green and Swets [1966]. In this original work, the participant's task was to discriminate signal trials from randomly intermixed nonsignal trials. In contrast to the SIAM procedure, participant's response does not determine the EF strength of the following trial. In signal (exposure) trials, AC EF ranging from 10 to 30 kV/m or DC EF ranging from 10 kV/m to 44 kV/m were presented. Depending on participant's response and similar to the SIAM procedure, four outcomes were possible: hit, miss, false alarm, and correct rejection (see Table 3). From this outcome, a person's ability to discriminate exposure from sham exposure (sensitivity d') could be calculated by $d' = z(\text{hit}) - z(\text{false alarm})$. For a consecutive z -transformation, hit rates and false alarm rates of 1 or 0 had to be corrected. Hautus [1995] recommended the log-linear method for which each number of hits and false alarms was increased by 0.5 and each number of exposure trials and sham exposure trials was increased by 1. This addition was not only applied to extreme values but to all hit and false alarm rates. The log-linear procedure is still a common method to correct for extreme hit and false alarm rates [Valuch and Mattler, 2019]. In this way, participant's sensitivity toward different EF strengths could be calculated. Green and Swets [1966] suggested that d' values equal or greater than 1 denote a difference of at least one standard deviation between the distribution of correct responses and false alarms. Consequently, d' values equal or greater than 1 reflect a successful detection of a given EF. d' values greater than 2 or 3 indicate a very good or excellent detection performance, respectively.

Test Procedure

Overall, 5 test days per participant were carried out. Per test day, only one participant was present performing eight sessions on average. On the first test day, we determined individual perception thresholds, while the other four days were used to investigate the influence of experimental (test days 2, 3, and 4) and environmental (test day 5) factors (see Table 4).

Each participant performed SIAM as well as SDT sessions, both consisting of the same number of exposure and sham exposure trials, following a randomized order to preclude sequence effects. Depending on participant's performance in SIAM sessions, the number of trials required to determine an individual detection threshold differed. Hence, the duration of SIAM sessions varied between 10 and 35 min. If no detection threshold could be estimated within 35 min, the SIAM session was terminated by the investigator. Additionally, the SIAM session

TABLE 1. AC EF Uniformity

AC E_{mean} (kV/m)	Variation of EF at measurement points (% of E_{mean})				
	MP1	MP2	MP3	MP4	MP5
3.2	0.0	0.5	-0.9	1.1	1.5
6.7	-1.6	2.1	-2.7	0.3	1.9
9.8	-0.4	1.3	-1.4	0.6	1.1
12.9	-0.1	1.4	-1.0	0.5	0.2
16.3	-0.1	0.9	-1.1	-0.9	1.2
19.7	0.6	0.6	-0.4	-1.3	0.5
23.0	-0.3	1.7	-1.3	-0.2	0.1
26.0	-0.4	1.4	-1.4	-0.4	0.7
29.3	-0.8	1.8	-1.8	-0.2	1.0

Mean AC EF (E_{mean}) and percentage variations from mean value at five MPs.

AC = alternating current; EF = electric field; MP = measurement point.

TABLE 2. DC EF and Ion Current Density Uniformity

DC E_{mean} (kV/m)	J_{mean} (nA/m ²)	Variation of EF at measurement points (% of E_{mean})					Variation of ion current density at measurement points (% of J_{mean})				
		MP1	MP2	MP3	MP4	MP5	MP1	MP2	MP3	MP4	MP5
13.8	46.7	-0.1	-2.1	1.9	3.4	-3.1	-2.4	-4.3	9.7	4.1	-7.0
27.1	178.6	-0.3	-0.3	2.0	0.7	-2.2	-4.9	-3.0	4.5	4.5	-1.1
39.0	322.0	-0.1	-3.8	2.8	1.4	-0.4	-9.1	8.1	7.3	-0.4	-5.9
49.1	462.4	-1.6	-2.5	1.4	0.3	2.4	-6.4	2.0	1.5	0.6	2.3

Mean DC EF (E_{mean}) and mean ion current densities (J_{mean}) as well as percentage variations from both mean values at five MPs. DC = direct current; EF = electric field; MP = measurement point.

stopped automatically if the maximum EF strength was not perceived three times consecutively or if the minimum EF strength could be correctly detected three times. In contrast, the duration of SDT sessions was more consistent, lasting about 25 min.

As in Blondin et al. [1996], each exposure trial within a session consisted of four consecutive periods (see Fig. 7). First, the EF increased from zero to the targeted EF strength during the increasing period. At the end of this period, full EF strength was reached and maintained during the exposure and response period. Participants were asked to report whether they could perceive an EF or not by pressing one of four response buttons within 5 s. Possible answers to the question “Do you perceive an electric field?” were “Yes—certain,” “Yes—uncertain,” “No—uncertain,” and “No—certain.” For the present results, only the Yes/No-dimension was considered. Following the response period, the EF decreased over a 7–9 s decreasing period. The next trial started without any delay. Besides the fact that no EF was applied, sham exposure trials followed the same procedure. Depending on the test condition, trial duration varied between 22 and 39 s.

Test Conditions

To investigate the influence of experimental and environmental factors on human EF perception, the ramp slope, exposure duration, ion current density, polarity, and relative humidity were modified on different test days (see Table 4). For each factor, two or three test conditions were

defined, such as low or high ramp slope, short, medium, or long exposure duration, positive or negative air ions combined with low, medium, or high ion current density, and low or high relative humidity. Due to technical constraints, for DC EF exposure, ramp slopes of 2.8 kV/m/s (low) and 12.5 kV/m/s (high), whereas for AC EF exposure, ramp slopes of 1.7 kV/m/s (low) and 7.5 kV/m/s (high) were used. Thus, the increasing period lasted 11.9 s (low ramp slope) or 2.5 s (high ramp slope). Varied exposure durations led to constant overall trial durations. When exposure duration was modified, durations of 4 s (short), 12 s (medium), and 20 s (long) were tested with constant ramp slopes of 12.5 kV/m/s (DC) and 7.5 kV/m/s (AC). To investigate the influence of air ions on EF perception, participants were exposed to positive and negative EFs without ion current or with ion current densities of 120 nA/m² (± 16 kV/m), 360 nA/m² (± 30 kV/m), and 540 nA/m² (± 44 kV/m) with constant ramp slopes of 12.5 kV/m/s (DC) and 7.5 kV/m/s (AC) and exposure duration of 10 s. Since relative humidity during ramp slope, exposure time, and air ion conditions was set to 50% at 22 °C, we explicitly aimed to explore its influence on EF perception. This was done by changing relative humidity to 30% and 70% using a constant ramp slope of 12.5 kV/m/s (DC) and 7.5 kV/m/s (AC) as well as an exposure duration of 5 s.

Per SDT session, one test condition was investigated under different EF strengths. Whereas AC EF were always presented in strengths of 10, 20, or 30 kV/m, DC EF strengths differed between test days due to technical problems. Therefore, when investigating the ramp slope, reduced DC EF strengths of 10, 20, and 30 kV/m were applied. However, when relative humidity, exposure duration, and air ions were examined, DC EF strengths were 16, 30, and 44 kV/m.

TABLE 3. Outcomes of a Signal Detection Task

	“Yes-response”	“No-response”
Exposure trial	Hit	Miss
Sham exposure trial	False alarm	Correct rejection

TABLE 4. Test Procedure

Test day	2	3	4	5
Experimental factor	Ramp slope	Exposure duration	Air ions and polarity	–
Environmental factor	–	–	–	Relative humidity
Test conditions	Low, high	Short, medium, long	Without, with; positive, negative	Low, high
Variations in kV/m	DC: 10, 20, 30 AC: 10, 20, 30	DC: 16, 30, 44 AC: 10, 20, 30	DC: ± 16 , ± 30 , ± 44 AC: 10, 20, 30	DC: 16, 30, 44 AC: 10, 20, 30

SDT setup for test days 2–5 is depicted. Each experimental/environmental factor contains two or three test conditions. Every test condition was filled with variations of EF strengths.

AC = alternating current; DC = direct current; EF = electric field; SDT = signal detection theory.

Statistical Analyses

Results obtained within the SIAM procedure were analyzed by using descriptive statistics. Detection thresholds of each participant were calculated by averaging the EF strengths for the last three reversals of each SIAM session. Additionally, the derived detection thresholds were averaged to obtain a mean value over all participants. After calculating a person's sensitivity by $d' = z(\text{hit}) - z(\text{false alarm})$ and correcting for extreme values according to the log-linear method [Hautus, 1995], overall mean values were also computed for the SDT procedure. These SDT overall mean values were used to conduct separated repeated measures analysis of variances (ANOVAs) for possible effects of the ramp slope, exposure duration, air ions, and relative humidity using SPSS 25 (IBM, Armonk, NY). The α level was set to 0.05 and when necessary Greenhouse–Geisser correction [Greenhouse and Geisser, 1959] was applied. As a measure of effect size, η^2 was reported.

RESULTS

Subjective Procedures

Cutaneous sensations induced by EF exposure were characterized very differently by the participants (see Table 5). Whereas six participants sensed a pleasurable tingling or a slight itching, four compared their sensation with having some ants on their skin (formication). Sensations perceived during DC EF and AC EF sessions did not vary widely except for three participants who reported unpleasant stinging, pinching, or burning during AC EF exposure. Nevertheless, no participant reported painful sensations. In contrast, most participants judged them to be even pleasant. Whereas the type of sensation was quite similar during DC EF and AC EF sessions, the affected body part differed significantly. DC EF were primarily perceived in the head area, especially scalp hair and face. However, AC EF exposure caused mainly sensations on limbs, such as arms, legs, and feet.

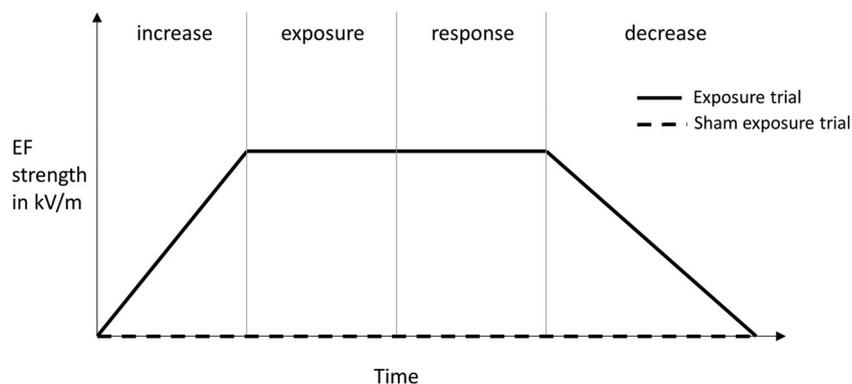


Fig. 7. Trial course. Each trial was divided into four consecutive periods (increase, exposure, response, decrease). In exposure trials, a specific EF strength was applied, whereas in sham exposure trials the EF was turned off. The duration of the increasing period and exposure period differed among test conditions. The response period and decreasing period lasted 5 s and 7–9 s, respectively. EF = electric field.

TABLE 5. Sensations During EF Exposure

	DC EF	Number of mentions	AC EF	Number of mentions
Sensation	Pleasurable tingling	6	Pleasurable tingling	6
	Slight itching	6	Slight itching	6
	Causes goose bumps	4	Slight vibration	4
	Slight vibration	4	Unpleasant stinging	3
	Formication	4	Like pinpricks	3
	Cooling	2	Formication	3
			Causes goose bumps	2
Location	Scalp hair	10	Unpleasant pinching	2
	Face	4	Unpleasant burning	2
	Arms	3	Arms	6
	Neck	2	Legs	5
	Legs	2	Feet	5
			Scalp hair	4
			Face	2
			Neck	2

Type of sensation and affected body part due to DC EF and AC EF exposure. Eleven participants were questioned. Multiple answers per participant were possible.

AC = alternating current; DC = direct current; EF = electric field.

Detection Thresholds

Overall detection thresholds determined by the SIAM procedure were 23.4 kV/m (SD: 4.3) for DC EF, 16.9 kV/m (SD: 6.0) for AC EF, and 11.4 kV/m (SD: 2.9) for hybrid EF exposure, indicating that the averaged detection threshold for hybrid EF exposure, i.e., co-exposure to 4 kV/m AC and 6–30 kV/m DC, was lower than that for AC or DC EF exposure alone (see Fig. 8, horizontal lines). The individual number of SIAM sessions (see small circles) varied between one and five. Each of the 10 participants (one dropped out) completed at least two SIAM sessions under AC EF exposure, whereas the overall mean detection thresholds (see large circles) for DC EF and hybrid EF exposure were based on the results of seven and six participants, respectively. Under DC EF exposure, the individual detection threshold of three participants could not be determined because two participants could not even perceive the minimum DC EF of 16 kV/m while one participant was not able to discriminate exposure trials of maximum EF strengths of 30 kV/m from sham exposure trials. For hybrid EF exposure, the detection thresholds of four participants could not be determined. The first three participants were co-exposed to 10 kV/m AC EF and 16–40 kV/m DC EF, but all of them were able to reliably perceive the minimum strength combination (10 kV/m AC and 16 kV/m DC). Thus, no detection threshold could be found. Subsequently, for all other participants, the applied EF strengths were adjusted to 4 kV/m AC EF and 6–30 kV/m DC EF. Additionally, the data of one participant under hybrid EF exposure was lacking due to technical problems. Taken together, thresholds for

DC EF, AC EF, and hybrid EF differed, leading to higher values for DC EF, whereas interindividual variance was increased under AC EF exposure.

Participant's Sensitivity d'

Ramp slope. A $2 \times 2 \times 3$ repeated measures ANOVA with the factors *ramp slope* (high, low), *field type* (DC, AC), and *EF strength* (10 kV/m, 20 kV/m, 30 kV/m) indicated no significant main effect of *ramp slope* ($p = 0.732$). However, significant main effects of *field type* ($F(1,10) = 8.79$, $p = 0.014$, $\eta^2 = 0.47$) and *EF strength* ($F(2,9) = 54.87$, $p = 0.000$, $\eta^2 = 0.85$) as well as a marginal significant interaction between the factors *ramp slope* and *EF strength* could be revealed ($p = 0.052$). As depicted in Figure 9, d' values of high ramp slopes were similar to those of low ramp slopes, indicating that the increasing period (see Fig. 7) had no effect on the detection threshold. For each EF strength, d' values of DC EF were lower than d' values of AC EF. Interindividual variations could be observed in both conditions. The majority of the participants were not able to reliably detect EF strengths (DC as well as AC) of 10 kV/m ($d' < 1$). However, for DC EF strengths of 20 kV/m, approximately half of all participants reached d' values greater than 1 and nearly all participants could perceive AC EF strengths of 20 kV/m. Finally, both DC and AC EF strengths of 30 kV/m could be reliably detected by all but one participant. In general, d' values could be assessed for each EF strength and increased with higher EF strengths, whereby AC d' values were constantly higher than DC d' values.

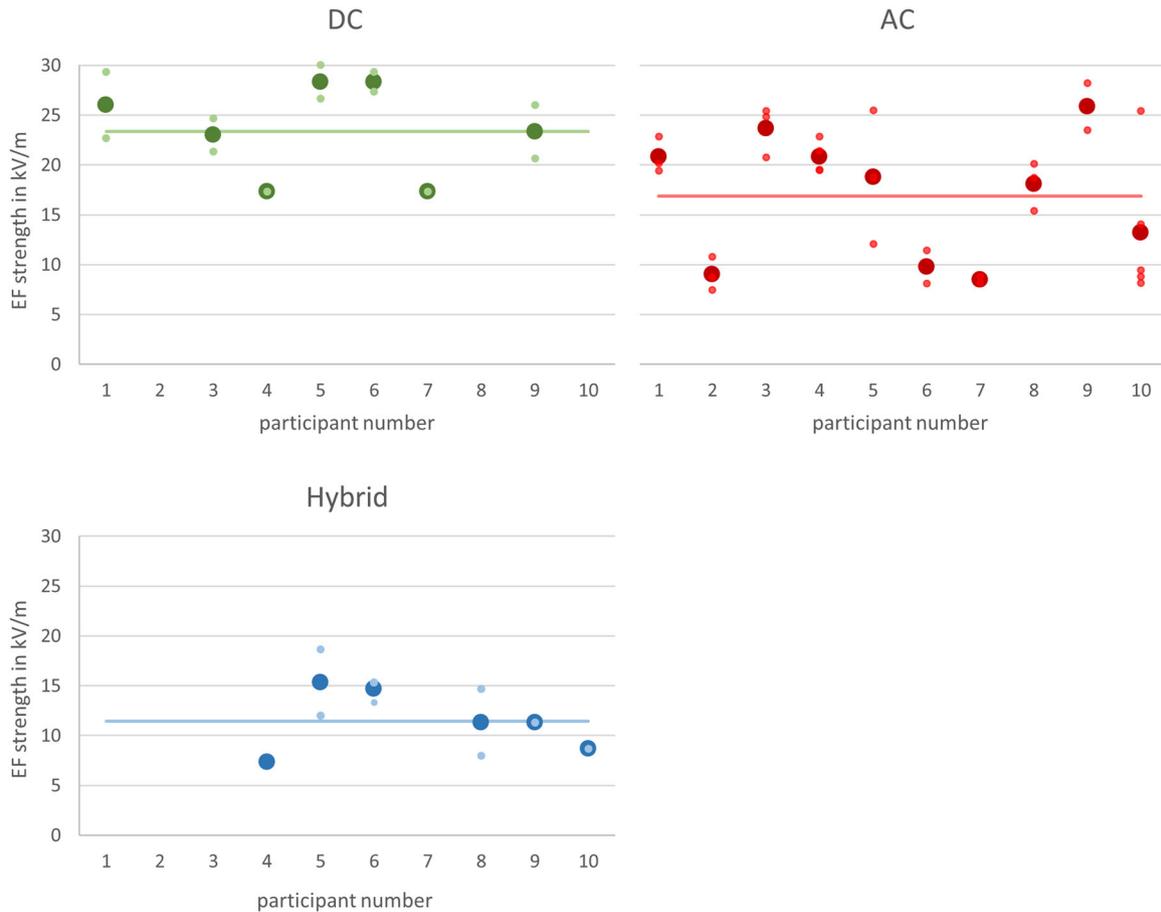


Fig. 8. SIAM detection thresholds. Averaged individual detection thresholds (large circle) based on the respective number of SIAM sessions (small circle) for DC EF, AC EF, and hybrid EF exposure. Lines indicate the averaged detection threshold over all participants. Data are lacking for participants 2, 8, and 10 for DC EF exposure and for participants 1, 2, 3, and 7 for hybrid exposure. During hybrid exposure, AC EF was set to 4 kV/m, while DC EF varied from 6 to 30 kV/m. AC = alternating current; DC = direct current; EF = electric field; SIAM = single-interval-adjustment matrix.

Exposure duration. The $3 \times 2 \times 3$ repeated measures ANOVA with the factors *exposure duration* (4 s, 12 s, 20 s), *field type* (DC, AC), and *EF strength* (DC: 16, 30, 44 kV/m; AC: 10, 20, 30 kV/m) did not show a main effect or interaction with the factor *exposure duration* (all $p > 0.159$), indicating that the different exposure durations had no effect on the detection threshold. However, a significant main effect of *field type* ($F(1,8) = 5.65$, $p = 0.045$, $\eta^2 = 0.41$) and *EF strength* ($F(2,7) = 40.22$, $p = 0.000$, $\eta^2 = 0.83$) as well as an interaction of both factors ($F(3,6) = 7.69$, $p = 0.005$, $\eta^2 = 0.49$) were found. Since d' values increased with higher EF strengths, EF perception seems to be facilitated by high EF strengths.

Air ions and polarity. A $2 \times 2 \times 3$ repeated measures ANOVA with the factors *ion presence* (no, yes), *ion/field*

polarity (positive, negative), and *DC EF strength* (± 16 kV/m, ± 30 kV/m, ± 44 kV/m) did not show a significant main effect of *ion presence* ($p = 0.11$) or *ion/field polarity* ($p = 0.62$), indicating that neither the presence of air ions nor ion/field polarity influenced the detection thresholds. However, a significant main effect of *DC EF strength* ($F(2,8) = 94.17$, $p = 0.000$, $\eta^2 = 0.91$) was revealed, supporting previous findings. Even if significance was not reached, d' values for DC EF with ion currents (16 kV/m: 0.9 [SD: 0.9], 30 kV/m: 2.2 [SD: 0.8], 44 kV/m: 2.8 [SD: 0.6]) were numerically higher than d' values for DC EF without ion currents (16 kV/m: 0.3 [SD: 0.5], 30 kV/m: 1.9 [SD: 0.6], 44 kV/m: 2.7 [SD: 0.6]) for each EF strength.

Relative humidity. The $2 \times 2 \times 3$ repeated measures ANOVA with the factors *humidity* (30%, 70%), *field type*

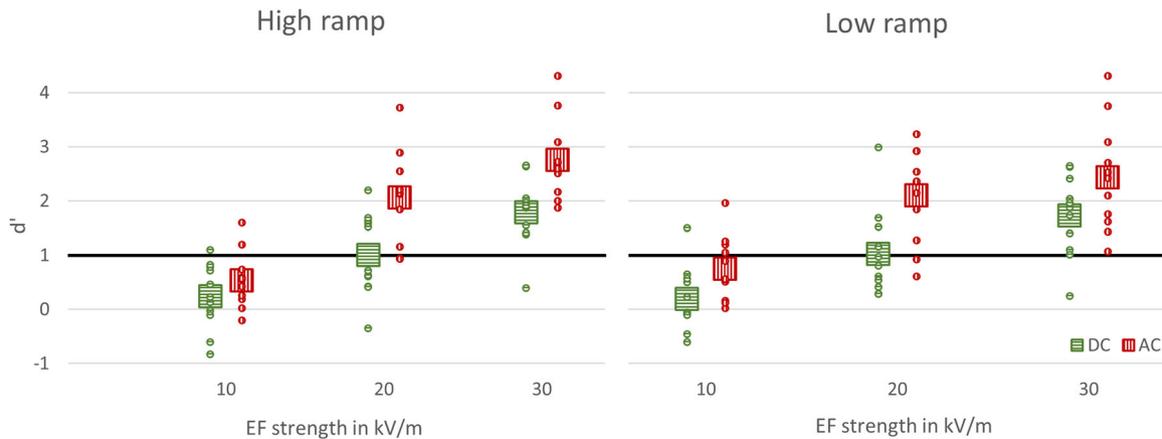


Fig. 9. The influence of ramp slope on sensitivity d' . Individual (circle) and averaged sensitivities (square) for EF strengths of 10, 20, and 30 kV/m for DC EF (green with horizontal stripes) and AC EF (red with vertical stripes) combined with high ramp slopes (left) and low ramp slopes (right) during the increasing period of a trial. Black lines represent d' of 1, which indicates a successful detection. AC = alternating current; DC = direct current; EF = electric field.

(DC, AC), and EF strength (DC: 16, 30, 44 kV/m; AC: 10, 20, 30 kV/m) showed a significant main effect of EF strength ($F(2,7) = 74.55, p = 0.000, \eta^2 = 0.90$) and two significant interactions: $humidity \times field\ type$ ($F(2,7) = 26.30, p = 0.001, \eta^2 = 0.77$) and $humidity \times EF\ strength$ ($F(3,6) = 4.47, p = 0.034, \eta^2 = 0.36$), indicating that the variation of relative humidity had an effect on detection thresholds. A reduced interindividual variation was observed with increasing EF strength for both AC EF and DC EF (see Fig. 10), suggesting a certain level of saturation. For each DC EF strength, averaged d' values of 70% relative humidity (16 kV/m: 1.1 [SD: 1.2], 30 kV/m: 2.1 [SD: 0.9], 44 kV/m: 2.8 [SD: 0.6]) were numerically higher than d' values of 30% relative humidity (16 kV/m: 0.5 [SD: 0.9], 30 kV/m: 1.3 [SD: 0.6], 44 kV/m: 2.1 [SD:

0.5]), showing that participants were able to detect DC EF strengths of 16 kV/m with relative humidity of 70% ($d' = 1.12$) but not when humidity was set to 30% ($d' = 0.47$). In contrast, for AC EF, d' values were lower for high humidity (10 kV/m: 0.6 [SD: 0.5], 20 kV/m: 2.0 [SD: 1.1], 30 kV/m: 2.7 [SD: 0.8]) than for low humidity (10 kV/m: 1.8 [SD: 1.4], 20 kV/m: 2.5 [SD: 1.2], 30 kV/m: 2.8 [SD: 0.9]) for each EF strength. The AC EF strength of 10 kV/m could only be perceived by the participants on average when relative humidity was set to 30% ($d' = 1.78$), but not when humidity was set to 70% ($d' = 0.57$). To summarize, the perception of DC EF seemed to be facilitated by a high humidity, whereas AC EF exposure could be better perceived under low relative humidity condition.

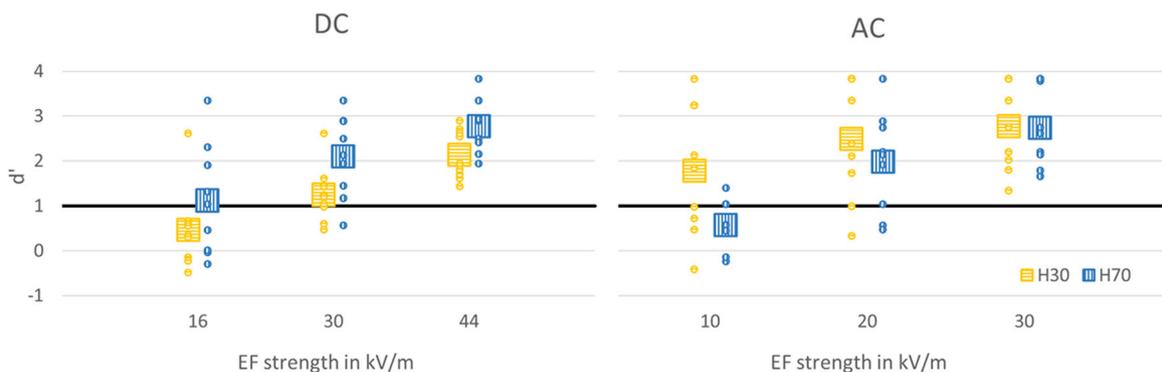


Fig. 10. The influence of humidity on sensitivity d' . Individual (circle) and averaged sensitivities (square) for EF strengths of 16, 30, and 44 kV/m for DC EF (left) and for EF strengths of 10, 20, and 30 kV/m for AC EF (right) under different humidity conditions. Relative humidity of 30% (H30) in yellow with horizontal stripes and relative humidity of 70% (H70) in blue with vertical stripes. Black lines represent d' of 1, which indicates a successful detection. AC = alternating current; DC = direct current; EF = electric field.

DISCUSSION

The aim of the current pre-study was to investigate the influence of experimental and environmental factors, such as the ramp slope, exposure duration, presence of air ions, and relative humidity, on human perception of EF. We evaluated first estimates of human detection thresholds for DC EF, AC EF, and hybrid EF under whole-body exposure as well as differences in human perception of DC EF and AC EF in terms of the type of sensation and affected body part. Thus, essential settings for a further large-scale experimental study were identified. Our results suggest that neither the ramp slope nor the exposure duration or the presence of air ions affected EF perception significantly. However, relative humidity seemed to be an environmental factor influencing the individual detection performance. Mean detection thresholds were lower for hybrid EF exposure (11.4 kV/m) than for AC EF (16.9 kV/m) and DC EF (23.4 kV/m) exposure alone. Moreover, individual detection thresholds and subjective sensations varied greatly between participants.

Since the experimental factors ramp slope and exposure duration did not affect the perception of EF, high ramp slopes of 12.5 kV/m/s (DC) and 7.5 kV/m/s (AC) as well as short exposure periods of about 4 s are appropriate for following studies with the advantage of preventing fatigue effects of participants. As ion/field polarity did not influence the EF perception, it is sufficient to apply one polarity (positive or negative) in further investigations. Each repeated measures ANOVA revealed a main effect of field strength, clearly indicating that high EF strengths facilitate the perception of EF. Furthermore, our data showed that d' values of DC EF exposure were lower than d' values of AC EF exposure for each EF strength, indicating that AC EF were perceived at lower EF strengths than DC EF. These results are consistent with the current data revealed by the SIAM procedure. Blondin et al. [1996] also calculated d' values for the detection of DC EF but d' values of about 1 were reported only for DC EF strengths of 40 kV/m. However, Blondin et al. [1996] did not provide any information concerning the correction for extreme hit and false alarm rates. Additionally, relative humidity was lower than 50% and varied between 6% and 40% in the previous study. In contrast to Blondin et al. [1996] reporting a decreased detection threshold of 36.9 kV/m (DC) under co-exposure to ion currents, we did not find a significant effect of ion presence on the perception of EF. However, our results indicate that ion currents seemed to influence EF perception at least numerically. Thus, further investigations with a

higher number of participants are needed to confirm the current data.

In accordance with Odagiri-Shimizu and Shimizu [1999], our data showed lower detection thresholds for DC EF with increased relative humidity, indicating that a higher humidity facilitates the perception of DC EF. However, our findings on higher AC EF perception thresholds under increased relative humidity are in contrast to the data of Kato et al. [1989], who revealed lower AC EF perception thresholds in combination with high humidity, at least for a limb exposure. Thus, these data need further investigation and confirmation in a future study, including a higher number of participants.

SIAM detection thresholds of 23.4 kV/m (DC EF) and 16.9 kV/m (AC EF) were consistent with the results of Clairmont et al. [1989] reporting thresholds of about 25 kV/m (DC EF) and 15 kV/m (AC EF) under overhead high-voltage transmission lines. In contrast, Blondin et al. [1996] found mean perception thresholds of 45.1 kV/m (DC EF) under controlled conditions. However, Blondin et al. [1996] assessed thresholds by averaging midrun estimates for five runs, whereas, in the current study, EF strengths for the last three reversals were averaged. Furthermore, in the study of Blondin et al. [1996], relative humidity was not constant at 50% but varied between 6% and 40%. As relative humidity seems to affect the perception of EF (see Fig. 10), the lower perception thresholds found in our study may be caused by higher humidity compared to the study of Blondin et al. [1996]. Whereas current AC detection thresholds (16.9 kV/m) were consistent with those under limb exposure [8–33 kV/m, Chapman et al., 2005], DC detection thresholds were much lower under whole-body exposure (23.4 kV/m) than under limb exposure [375 kV/m, Odagiri-Shimizu and Shimizu, 1999]. This might be explained by a field increase at the top of the body about a factor of 13–18 under whole-body exposure [Petri et al., 2017], similar to the field increase under high-voltage transmission lines. In accordance with the results of Clairmont et al. [1989], EF detection seems to be supported by the co-exposure of AC EF and DC EF since we found a lower detection threshold for hybrid exposure (11.4 kV/m) than for DC EF (23.4 kV/m) and AC EF exposure (16.9 kV/m) alone. Overall, intraindividual variances were lower compared to the interindividual variances.

Participants included in our study reported similar subjective sensations as participants of previous studies [Clairmont et al., 1989; Blondin et al., 1996], such as tingling or itching, and localized the sensations caused by DC EF exposure primarily at the head area. Chapman et al. [2005] exposed participant's arms to DC EF of up to 65 kV/m and AC EF of up to 35 kV/m. None of the participants were able to detect DC EF on their arms,

whereas AC EF could reliably be perceived by a majority of participants [Chapman et al., 2005]. Odagiri-Shimizu and Shimizu [1999] exposed participant's arms to DC EF of up to 450 kV/m and measured mean detection thresholds of approximately 375 kV/m, indicating that only high EF strengths could be perceived on arms. These results support the hypothesis that DC EF could better be perceived in the head area compared to AC EF, which was perceived on limbs by most of the participants. That might be explained by the different characteristics of both field types. Whereas DC EF mainly leads to charge accumulations at the scalp hair, AC EF causes more vibrations of a tiny hair and is therefore easier to perceive on limbs.

Limitations

The main limitation of the current pre-study is the small number of 11 participants, particularly regarding the large interindividual variations in detection thresholds. Therefore, current results have to be considered as estimates for detection thresholds that have to be defined precisely in following large-scale investigations. Furthermore, the DC detection thresholds of three participants were not in the range of DC EF strengths tested within the SIAM procedure. Hence, the overall mean threshold is based only on the results of participants with thresholds in the applied range. Due to an unadjusted hybrid EF range (10 kV/m AC and 16–40 kV/m DC) applied for the first three participants, the thresholds for these participants could not be determined because each of them was not able to reliably detect even the minimum EF combination. Since the human perception of hybrid EF under controlled conditions and whole-body exposure has not been investigated before, it was necessary to find appropriate EF strength combinations covering the human perception range. The adjusted EF strengths of 4 kV/m AC and 6–30 kV/m DC should be applied in further investigations.

CONCLUSION

With the current pre-study, we were able to provide new insights into the characteristics of whole-body EF perception under highly controlled conditions. The most important experimental and environmental predictors for DC EF, AC EF, and hybrid EF perception, such as an appropriate ramp slope and exposure duration, were determined. Our results confirm previous studies as relative humidity and the co-exposure to DC EF and AC EF seemed to facilitate the perception of EF [Clair-

mont et al., 1989; Odagiri-Shimizu and Shimizu, 1999]. Further research on this and the influence of air ions is required. Mean detection thresholds were consistent with the results of previous studies [Clairmont et al., 1989; Blondin et al., 1996]. However, mean detection thresholds should be considered as estimates and have to be defined precisely in following large-scale examinations. Further investigations, including a sufficient number of participants of all ages, are needed to determine statistically verified detection thresholds of the population that could form the basis for recommendations regarding acceptable limit values of EF.

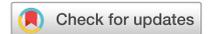
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OPEN

The role of the AC component in human perception of AC–DC hybrid electric fields

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Electric energy is essential to today's society. To cope with global higher demand while minimizing land use, efficient high voltage direct current (HVDC) power lines are planned to be mounted on existing alternating current (AC) structures leading to electric fields (EFs) from both AC and DC transmission lines in hybrid configurations. Due to the close proximity to residential areas, the investigation of human hybrid EF perception and underlying mechanisms will be useful to project permitting. To specify the influence of the AC component on the whole-body detection thresholds of hybrid EFs and to explore the lower bound of human hybrid EF perception, 51 participants with an EF detection ability above average were exposed in a double-blind laboratory study. A psychophysical method based on the signal detection theory was used. Very low EF strength combinations, e.g. 1 kV/m AC combined with 1 kV/m DC, were reliably perceived by at least one participant. Detection thresholds were significantly lower with increased AC EF strengths, underlining the key role of the AC component in the human perception of hybrid EFs. Findings will contribute to the assessment of public reaction to the perception of EFs around hybrid overhead power lines and to their optimal designs.

In recent years, the technology for energy production and delivery has remarkably changed. New techniques of generating energy, especially from renewable power sources, combined with efficient high voltage direct current (HVDC) power lines were established to cope with higher long-distance transmission needs for electricity between generation and consumption areas. HVDC overhead power lines have already been built, especially in rural areas¹. Now, to reduce costs and minimize the impact on the landscape and the need for new rights-of-way in built-up areas, HVDC lines are planned to be mounted on existing high voltage alternating current (HVAC) structures leading to AC–DC hybrid electric fields (hybrid EFs)². Due to the close proximity to industrial and residential areas, the thresholds for human perception of hybrid EFs are of great interest. Moreover, no agency has proposed limit values for hybrid EF exposures.

Humans are able to reliably detect EFs^{3,4}. So far, no specific receptors or signal transduction pathways have been clearly identified. However, hair receptors used for detection of vibration on hairy skin seem to be crucial for EF perception^{5,6}. As Reilly suggested, the movement of charges along the hair shaft of a hydrated hair might lead to mutual repulsion between single hair follicles resulting in a perceptible vibration⁴. This process of AC EF perception is thought to be facilitated by an increased relative permittivity of body hair⁷. Interestingly, in a recent study, we found that higher skin moisture did not result in facilitated EF perception, at least when it was assessed at a single measurement point before starting the EF perception testing⁸. Moreover, body surface sensibility seems to be another important factor influencing EF perception. Kursawe et al. recently demonstrated a relationship between vibrotactile measures (31 Hz and 63 Hz) and the detection of AC EFs and hybrid EFs⁸. The authors explained the correlation with hybrid EFs by the kind of evoked sensation, i.e., tingling, itching, or vibration and stressed the importance of body surface sensibility in the interaction mechanism of EF perception⁸. Since large interindividual differences were found in human EF perception³, it is likely that differences in body surface sensibility or the length, structure, and relative permittivity of body hair all may influence individual EF perceptions.

To date, only a few experimental studies have focused on human perception of EFs. Local EF exposure showed rather heterogeneous detection thresholds of about 375 kV/m for DC EFs and 8–33 kV/m for AC EFs^{5,6}. Under whole-body exposure and laboratory conditions, DC detection thresholds were estimated between 18.7 and

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45.1 kV/m and decreased when ion currents were simultaneously generated^{8,9}. Whole-body exposure only to AC EF produced detection thresholds between 14 and 25 kV/m^{4,8}. The first investigations of human perception of hybrid EFs from overhead test lines were conducted by Clairmont et al.¹⁰. An unspecified number of participants were asked to judge the sensation level of EFs while standing under AC–DC overhead power lines. Averagely, a hybrid EF of 15 kV/m DC and 5 kV/m 60-Hz AC was rated as just perceptible¹⁰. Both increased DC EFs and increased AC EFs led to higher ratings of sensation levels in hybrid EFs. As the average perception rating of DC EFs alone was in the range of 20–25 kV/m, this nonblinded experimental field study provided the first hints that combined AC–DC EFs led to enhanced EF perception compared to either EF taken separately¹⁰. Increased sensation levels in hybrid EFs were also assessed when exposing four participants in a hybrid environment chamber¹¹. In line with these findings, Kursawe et al. determined decreased detection thresholds of 6.76 kV/m DC combined with 4 kV/m 50 Hz AC under hybrid condition compared to detection thresholds of single DC EF or AC EF presentation (DC: 18.69 kV/m, AC: 14.16 kV/m) testing 203 participants in a well-controlled, double-blind laboratory study⁸. The results confirm differences between single EF and hybrid detection threshold estimates as described in our preliminary study¹². This synergistic effect of the combined exposure of DC and AC EFs on human perception was supported by 40% of the participants being able to detect the lowest EF strength combination of 2 kV/m DC and 4 kV/m AC⁸. Within this first systematic examination of human hybrid EF perception, our group assessed facilitated detection performances in hybrid EFs when adjusting the DC component to higher EF strengths while keeping the AC EF constant at 4 kV/m.

In the current study, we aimed to specify the role of the AC component in the human perception of hybrid EFs. Fifty-one participants with a hybrid EF detection ability above average who participated in our previous study were exposed under highly controlled conditions to explore the human perception of low hybrid EFs. A secondary objective was to evaluate the influence of vibrotactile perception and skin moisture on EF perception, whereby skin moisture was repeatedly measured throughout the test day.

Methods

Participants. In this study, 51 healthy participants (20 men and 31 women) at the ages of 23 to 77 (mean 49.14, SD 17.52) were recruited from participants in our earlier study⁸. The requirement for participation was the ability to detect hybrid EF strength combinations of at least 4 kV/m AC and 8 kV/m DC, which was tested in the previous investigation. From 92 participants fulfilling this criterion, 51 responded to our invitation and were included in the study. Based on the medium effect size in previous research⁸, we calculated a test power of 99% to find an effect of EF strength. Exclusion criteria were electronic implants or indelible piercings, pregnancy, self-reported electrosensitivity, skin diseases, as well as psychiatric or neurological disorders. Signs of infection, as well as cutaneous or cardiovascular abnormalities, and medication or drug abuse were ruled out during the physical evaluation at the beginning of each test day. Risks and benefits of the study were thoroughly explained and all participants gave their written informed consent. The expense allowance was 100 Euro per participant. The ethics committee of the Medical Faculty of RWTH Aachen University approved the study (EK 065/20), which was conducted according to the Declaration of Helsinki without preregistration.

Exposure laboratory. EF perception tests were performed in a specially designed exposure laboratory, which was constructed at the University Hospital RWTH Aachen in cooperation with the Institute for High Voltage Equipment and Grids, Digitalization and Power Economics, RWTH Aachen University. A detailed description of the facility and the technical setup has been described in Jankowiak et al.¹². In the middle of the 16 square meter exposure laboratory, a height-adjustable chair was installed (see Fig. 1). To avoid charge accumulations at the chair and the walls, laminated densified wood was used. Monitoring electrodes were placed on both ankles of the participants via low resistive connections to record induced body currents during exposure and to ensure a connection to the ground. To provide homogeneous test conditions, all participants were set to the same head height by adjusting the chair. Additionally, an intercom system transmitted all sounds from the exposure laboratory to the adjacent investigator room and allowed a direct communication with the participants. Background noise generated by the high-voltage system was masked by a 65.8 dB(A) incoherent white noise played in the exposure laboratory during experimental testing.

Four high-voltage electrodes in the ceiling of the exposure laboratory were used to generate EFs. In this study, various hybrid EFs with a 50 Hz AC component of up to 4 kV/m (in the current work, AC EF strengths always refer to rms values) and a DC component of up to 16 kV/m were generated by an aluminum electrode, which was energized by a 34 kV AC transformer combined with a 200 kV DC source. To generate a homogenous EF to the base plate on the floor, 14 grading electrodes were mounted on the walls one below the other connected via ohmic-capacitive grading units. Several calibration and check-up measurements before or after experimental testing ensured the correct generation of the required EF. A field-mill type probe was used to calibrate the applied DC EF, while the measured displacement current enabled the calculation of the AC EF. Both, AC EF and DC EF uniformity were similar to those measured in previous studies¹². A proper functioning of the EF generating system was ensured by a laboratory technician.

For safety reasons, two cameras filmed the exposure laboratory permanently. Further security measures, such as light barriers around the participant's chair and a seatbelt equipped with contact plugs at both ends, were implemented to ensure a sufficient safety distance towards the electrodes at any time. An interruption of both the light barriers and the contact plugs of the seatbelt led to a shut-down of the EF generating system within 180 ms. Furthermore, pressing one of the three emergency stops, placed next to the participant, the investigator, and the laboratory technician, immediately stopped the experimental testing.

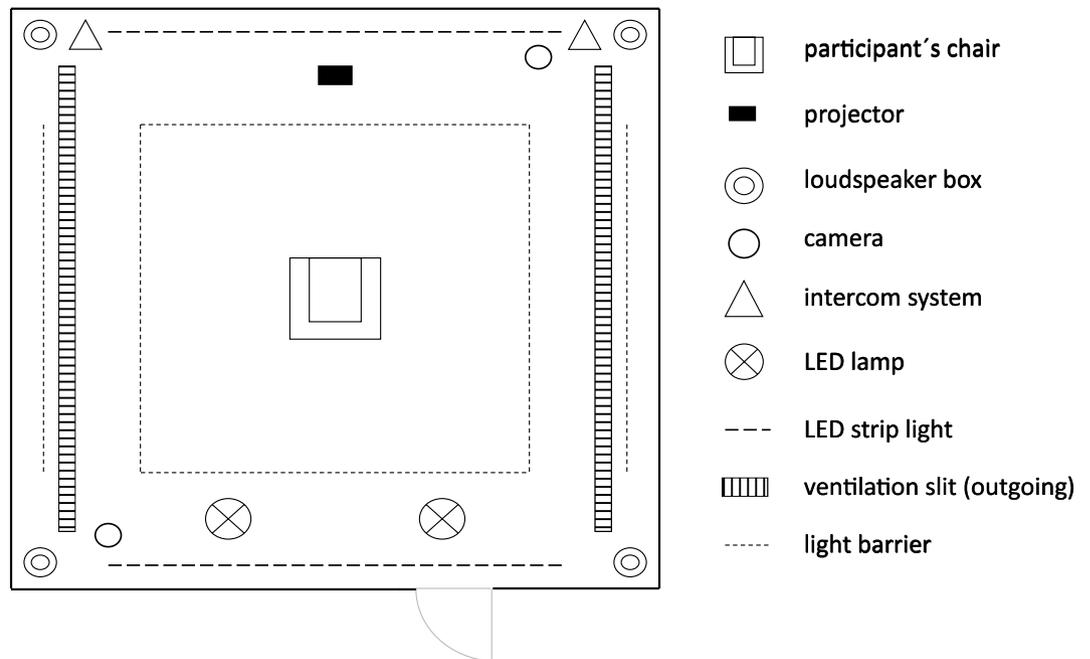


Figure 1. Schematic top view of the exposure laboratory. Adapted from Jankowiak et al.¹².

Measures of skin moisture and vibrotactile perception. To investigate the influence of individual factors on the perception of EFs, skin moisture and vibrotactile perception were recorded. Five measurements of skin moisture were conducted without parallel EF exposure throughout the test day to track possible variations and ensure a temporal proximity to EF exposure. Each measurement was performed three times on both insides of the forearms using a corneometer (CM 825; Courag + Khazaka electronic, Cologne, Germany). Skin moisture values were indicated dimensionless. Prior to the first EF exposure, vibrotactile perception was assessed with a perception meter (HVLab, Institute of Sound and Vibration Research, University of Southampton, Southampton, England). Vibrotactile perception was measured at 16, 40, 50, 63, and 200 Hz to cover a wide frequency range while focusing on the 50 Hz range. Participants were asked to press a button as long as they were perceiving a vibration in the right index finger. Pressing the button led to a decreasing amplitude of the vibration frequency, while not pressing the button was directly connected to an increasing amplitude until participants were again perceiving the vibration. Six reversals were used to calculate a mean value for each vibration frequency.

Psychophysical method for EF detection. Analyses of psychophysical measures based on the signal detection theory (SDT), introduced by Green and Swets¹³, were used to estimate the participant's ability to detect EFs and to calculate detection thresholds. The participant's task was to discriminate a fixed number of exposure trials (EF present) from the same number of randomly intermixed sham trials (no EF present) by pressing a button on a response pad. Four different outcomes were possible depending on the participant's response. An exposure trial could either be detected correctly (hit) or not perceived (miss). In line with this, sham trials could be classified as falsely perceived (false alarm) or correctly denied (correct rejection). To calculate the individual sensitivity (d') towards a given EF, the relative proportion of hits and false alarms were z-transformed and subtracted [$d' = z(\text{hit}) - z(\text{false alarm})$]. Hit rates and false alarm rates of 0 and 1 were corrected by the log-linear procedure to enable a z-transformation^{14,15}. A successful detection of a given EF was assumed when d' values equal or greater than 1 were reached. While d' values between 1 and 2 reflect a successful detection performance, d' values greater than 2 refer to a good sensitivity.

Test procedure. Four different test conditions were designed with constant AC EF strengths of 1, 2, 3, or 4 kV/m (rms values) at a frequency of 50 Hz combined with varying DC EF strengths of 1, 2, 4, 8, or 16 kV/m leading to various total EF strengths (see Table 1). Each test condition was randomly carried out in two sessions with randomized trial sequence. Therefore, each participant performed eight sessions on a single test day. Within each session, 50% sham trials were randomly interspersed to ensure the correct usage of the SDT method. A double-blind experimental setup in which neither the participant nor the investigator was aware of the trial sequence within a given session was established under computer control.

One session lasted about 15 min and consisted of 40 trials. The length of each trial was fixed and independent of the applied EF strength. Within 3 s, the EF was increased from zero to the target EF strength and remained constant for 5 s. Then, a question was projected on the wall in front of the participants that asked if they perceived an electric field. During the 4 s response period, the desired EF strength was maintained. Participants answered by pressing a button on the response pad and could choose from four options: "Yes-certain", "Yes-uncertain", "No-uncertain", and "No-certain". Thereafter, the EF decreased within 7–9 s and the next trial started immediately.

	AC EF strength (kV/m)	DC EF strength (kV/m)	Total EF strength (kV/m)
Condition 1	1	1, 2, 4, 8, or 16	1.41, 2.24, 4.12, 8.06, or 16.03
Condition 2	2	1, 2, 4, 8, or 16	2.24, 2.83, 4.47, 8.25, or 16.12
Condition 3	3	1, 2, 4, 8, or 16	3.16, 3.61, 5.00, 8.54, or 16.28
Condition 4	4	1, 2, 4, 8, or 16	4.12, 4.47, 5.66, 8.94, or 16.49

Table 1. Four different test conditions were designed with constant 50 Hz AC EF strengths of 1, 2, 3, or 4 kV/m (rms values) and varying DC EF strengths of 1, 2, 4, 8, or 16 kV/m. Total EF strengths were calculated by $\sqrt{E_{DC}^2 + E_{AC}^2}$. Each test condition consisted of two sessions with 20 exposure trials and 20 sham trials, respectively, whereby trial sequence differed in the second presentation.

Sham trials followed the same timing, but no EF was applied. During the whole test day, the temperature and the relative humidity in the exposure laboratory were constant at 22 °C and 50%, respectively.

Data processing and statistical analyses. Based on the d' values derived from the SDT procedure, individual psychometric functions regarding the hybrid EF perception ability were calculated for each test condition. Referring to Kursawe et al.⁸, total EF strengths were calculated by $\sqrt{E_{DC}^2 + E_{AC}^2}$ (see Table 1). Using linear interpolation, individual detection thresholds were determined, defined as the calculated EF strength where $d' = 1$ was reached. Two constraints had to be considered: no detection threshold could be estimated when participants did not reach a $d' \geq 1$ in any EF strength or when participant's data distribution over all EF strengths was inconsistent, e.g. a $d' \geq 1$ for 5 and 8.54 kV/m, but a $d' < 1$ for 16.28 kV/m. Individual detection thresholds were averaged.

Skin moisture values, d' values, and detection thresholds were analyzed in separate repeated measures analyses of variances (rm ANOVAs) using SPSS 25 (IBM, Armonk, NY). For rm ANOVAs on detection thresholds, the number of participants was reduced to $n = 19$, because data of 19 participants met preconditions for the calculation of detection thresholds in each test condition. The alpha level of $p = 0.05$ was accepted for significance. When sphericity was violated, Greenhouse–Geisser correction was applied and uncorrected degrees of freedom with corrected F and p values were indicated¹⁶. Partial eta-squared (η_p^2) values were used as a measure of effect size. Non-parametric correlations between the measures of individual factors and detection thresholds of each test condition were computed using Spearman's ρ . The level of significance was corrected according to Bonferroni.

Results

Averaged d' sensitivities of all EF strength combinations are illustrated in Fig. 2. The rm ANOVA with the factors AC EF strength (1, 2, 3, 4 kV/m) and DC EF strength (1, 2, 4, 8, 16 kV/m) showed a significant main effect of AC EF strength ($F(3, 150) = 38.96, p < 0.001, \eta_p^2 = 0.44$), as well as DC EF strength ($F(4, 200) = 99.39, p < 0.001, \eta_p^2 = 0.67$), and an interaction effect ($F(12, 600) = 4.47, p < 0.001, \eta_p^2 = 0.08$). Planned pairwise comparisons showed significant differences between all AC EF strengths (all p 's < 0.02). Except for the lowest DC EF level (1 and 2 kV/m), all DC EF strengths significantly differed as well (all p 's < 0.02). As sensitivities of $d' \geq 1$ reflect a successful detection, eight EF strength combinations were averagely perceived (4 kV/m AC with 4 kV/m DC; 2, 3, and 4 kV/m AC with 8 kV/m DC; all AC EF strengths with 16 kV/m DC). In general, both higher AC EF strengths and higher DC EF strengths increased d' values. These effects correspond to the increased number of participants who successfully detected the respective EF strength combination with both higher AC EFs and higher DC EFs (see Table 2). Whereas only one participant showed a successful perception of the lowest EF strength combination (1 kV/m AC and 1 kV/m DC), 43 participants were able to detect the highest EF strength combination of 4 kV/m AC and 16 kV/m DC.

Based on the total EF strengths and the interpolation of individual sensitivity indices, reduced detection thresholds were observed with increased AC EF strengths (see Fig. 3). Averaged detection thresholds were 8.89 kV/m (SD 3.40), 7.82 kV/m (SD 3.17), 6.48 kV/m (SD 2.84), and 5.70 kV/m (SD 2.21) for test condition 1, 2, 3, and 4, respectively. The rm ANOVA on the four detection thresholds revealed a significant main effect ($F(3, 54) = 20.55, p < 0.001, \eta_p^2 = 0.53$) underlining the substantial influence of the AC component on the hybrid EF perception.

Two individual factors and their hypothesized association with EF perception were investigated (skin moisture and vibrotactile detection). Skin moisture was measured at five measurement points (MPs) throughout the test day and mean values of both arms were 55.38 (SD 15.42), 51.41 (SD 12.48), 51.97 (SD 13.63), 50.86 (SD 11.75), and 51.29 (SD 13.10) for MP1, MP2, MP3, MP4, and MP5, respectively. The rm ANOVA with the factor Time (MP1, MP2, MP3, MP4, MP5) revealed a significant main effect ($F(4, 200) = 8.44, p = 0.001, \eta_p^2 = 0.93$). Pairwise comparisons showed significant differences between MP1 and MP2, MP4, and MP5 (all p 's < 0.05) underlining significantly increased values at MP1. A conclusive link between skin moisture and detection thresholds was not found, though (all p 's > 0.68). Mean vibrotactile detection thresholds were 0.09 dB (SD 0.06), 0.24 dB (SD 0.14), 0.38 dB (SD 0.30), 0.47 dB (SD 0.40), and 0.43 dB (SD 0.48) for vibration frequencies of 16, 40, 50, 63, and 200 Hz, respectively. However, significant correlations between vibrotactile scores and detection thresholds could not be found (all p 's > 0.2).

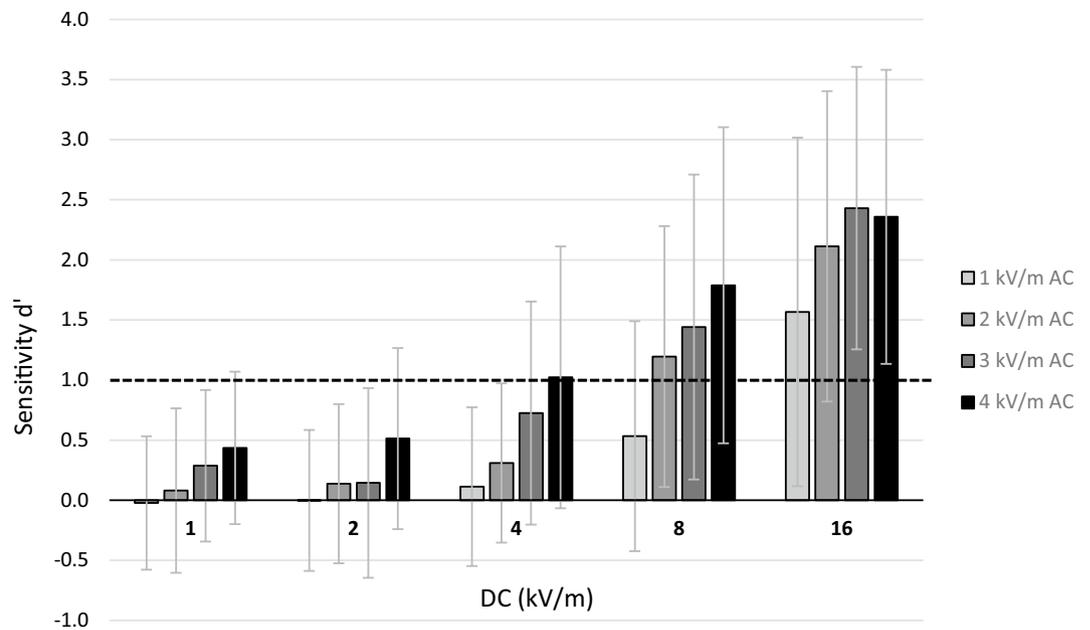


Figure 2. Influence of the AC component on DC sensitivities. Averaged sensitivities (d') for AC EF strengths of 1, 2, 3, and 4 kV/m combined with DC EF strengths of 1, 2, 4, 8, and 16 kV/m. Bars reflect standard deviations. Black line represents d' of 1 indicating a successful detection.

AC (kV/m)	DC (kV/m)				
	1	2	4	8	16
1	1	3	2	14	30
2	4	3	6	29	42
3	9	7	14	29	42
4	11	13	25	35	43

Table 2. Number of participants (out of $n = 51$) who successfully detected the respective EF strength combination ($d' \geq 1$).

Discussion

The current study aimed to specify the role of the AC component in the human perception of hybrid EFs. Fifty-one participants with a hybrid EF detection ability above average were exposed under highly controlled conditions to explore the human perception of low hybrid EFs. Detection thresholds of hybrid EFs were significantly lower with increased AC EF strengths and even very low EF strength combinations of up to 1 kV/m AC EF combined with 1 kV/m DC EF were reliably perceived by at least one participant ($d' > 1$). Correlations between vibrotactile detection thresholds and detection thresholds of hybrid EFs could not be replicated.

Both the sensitivity values and the number of participants who successfully detected the respective EF strength combination were higher with increased EF strengths, which also was reported in previous studies^{8,9,12}. The factor AC EF strength, as well as DC EF strength, showed a significant main effect. Therefore, both EF types substantially influenced the hybrid EF perception, which is in line with previous findings^{10,11}. The interaction effect of both factors was triggered by a constant performance of the participants at 2 and 3 kV/m AC with 2 kV/m DC, a lower performance at 4 kV/m AC with 16 kV/m DC compared to 3 kV/m AC with 16 kV/m DC, and a lower performance at 3 kV/m AC with 2 kV/m DC compared to 3 kV/m AC with 1 kV/m DC; bearing in mind that the two last differences were based on subthreshold sensitivity values.

This facilitating effect on the hybrid EF perception with increases in either the AC EF strength or the DC EF strength also was evident from the number of participants who were able to detect the respective EF strength combination ($d' \geq 1$) (see Table 2). Only one participant could successfully detect the lowest EF strength combination of 1 kV/m AC and 1 kV/m DC. Therefore, each EF strength combination was reliably detected by at least one participant underlining the human sensitivity to hybrid EFs. However, eight participants did not succeed in perceiving the highest EF strength combination of 4 kV/m AC and 16 kV/m DC. According to the inclusion criterion that hybrid EFs of at least 4 kV/m AC and 8 kV/m DC had to be reliably perceived in previous investigations, these participants did not meet expectations based on their performance in an earlier study⁸. This deviation might be explained by an altered EF strength presentation, which influenced the participant's performance: In the current study, participants were exclusively exposed to low hybrid EFs, whereas in previous investigations,

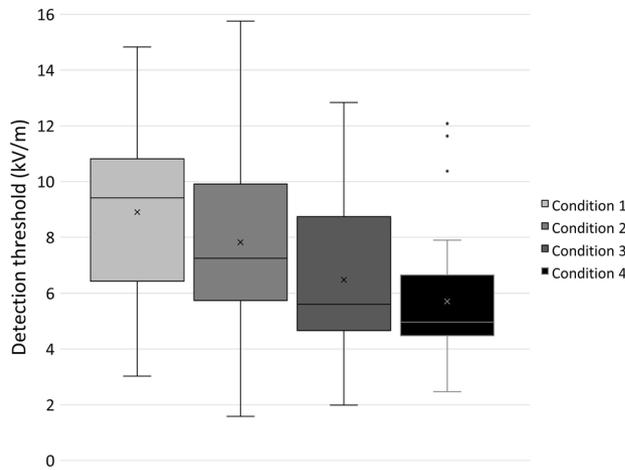


Figure 3. Boxplot diagrams with detection thresholds for all test conditions (DC EF strengths in all conditions were 1, 2, 4, 8, or 16 kV/m; AC component varied between conditions but was constant during one condition: 1 kV/m in Condition 1, 2 kV/m in Condition 2, 3 kV/m in Condition 3, and 4 kV/m in Condition 4). Detection thresholds based on total EF strengths ($\sqrt{E_{DC}^2 + E_{AC}^2}$). Number of participants, on which the estimated detection thresholds are based, were 26, 38, 34, and 33 for Condition 1, 2, 3, and 4, respectively. Crosses indicate averaged detection thresholds. Median values are expressed by the horizontal bar within the boxes. Dots represent outliers. Whiskers indicate the minimum and the maximum value of each data set.

hybrid EF strength combinations of up to 4 kV/m AC combined with up to 24 kV/m DC were presented, as well as single AC and DC EFs with a maximum of 30 kV/m and 38 kV/m, respectively. Based on this altered context, especially the missing strong EFs, the clear discrimination between exposure and sham trials was probably not as easy as in the previous participation for some participants. Hence, other sensations might have been misinterpreted as EF perception resulting in d' sensitivity indices below 1.

Differences between our detection thresholds and those assessed in other studies^{8,10} were mainly based on different calculation methods of detection thresholds and different test group populations. Kursawe et al.⁸ exposed an age- and sex-balanced group without prior experience in EF perception, while we only included participants who were evidently able to detect low hybrid EFs. Moreover, in the current study, detection thresholds were determined after calculating total EF strengths by $\sqrt{E_{DC}^2 + E_{AC}^2}$, whereas Kursawe et al.⁸ and Clairmont et al.¹⁰ estimated single DC detection thresholds for constant AC EF strengths. For specifying the role of one EF component, such as the AC component, detection thresholds based on the total EF strength were more suitable. Increasing the constant AC EF strength in each test condition (1, 2, 3, and 4 kV/m) led to substantially decreased detection thresholds of hybrid EFs (see Fig. 3). Therefore, the AC component plays a key role in the human perception of hybrid EFs. In the current study, 30 participants showed a successful perception at a total EF strength of 16.03 kV/m including 1 kV/m AC, while 42 participants were able to reliably perceive a total EF of 16.12 kV/m including 2 kV/m AC (see Table 2). As hybrid EF perception is facilitated by a higher AC component, it should be considered that not only the total EF strength but the EF composition of AC and DC EF strengths is decisive for estimating hybrid detection thresholds, particularly in the light of mutual influence of both components². Furthermore, the synergistic effect of AC and DC on EF perception, revealed in previous studies⁸, was verified by a significant main effect of the detection thresholds. Increased sensation levels in hybrid EFs combined with more vibrations of raised body hair were also observed previously¹¹. Theoretical calculations indicated that the electric force on body hair is up to three times higher in hybrid EFs compared to single AC or DC EFs¹⁷, which might be a possible explanation for the increased hybrid EF perceptions.

In line with previous findings^{8,9}, we revealed interindividual variances that might be partially based on physiological properties. Our data indicated that skin moisture values did not remain constant throughout the test day but were significantly higher at the beginning of the day, which could be based on initial excitement or previous activity. As in Kursawe et al.⁸, we did not find a correlation between skin moisture and EF perception. However, several studies have shown a conclusive link between hair moisture and EF perception^{6,7,11}. In our study, measurements of skin moisture on glabrous skin may not reflect actual hair moisture content. In contrast to Kursawe et al.⁸, we did not find a correlation between vibrotactile thresholds and detection thresholds of hybrid EFs. This could be caused by the reduced dataset of participants, who met the preconditions for the calculation of detection thresholds (see Fig. 3). Since evoked sensations were shown to be mainly dependent on movement of hair and the detection of vibrations^{5,6,11}, future investigations with more participants will help to identify receptors or signal transduction pathways of human EF perception.

Limitations. When interpreting the detection thresholds of the current study, it is important to note that only participants with a very good ability to detect hybrid EFs (successful detection of 4 kV/m AC combined with 8 kV/m DC in previous investigations) were included in order to explore the lower bound of hybrid EF

perception. Hence, the current detection thresholds are derived from a special group of participants and cannot be transferred to the entire population. In addition, participants were grounded during the exposure. Thus, detection thresholds reported in the current study may differ from detection thresholds when participants were partially or wholly isolated from ground as might apply to the public walking near or under HV transmission lines. Moreover, detection thresholds were calculated based on a reduced number of participants due to some preconditions. If participants did not successfully perceive even the highest EF strength within a given session, no individual detection threshold could be estimated. Furthermore, the rm ANOVA on detection thresholds was conducted based on a reduced number of participants because individual detection thresholds in all four test conditions could be estimated only for 19 participants.

Conclusion

Within the current study, we showed that the AC component plays a key role in the human perception of hybrid EFs as increased AC EF strengths lowered detection thresholds of hybrid EFs. Therefore, not only the total EF strength but especially the AC component in a hybrid EF is decisive for estimating hybrid detection thresholds. Focusing on the lower bound of hybrid EF perception, it could be indicated that some people are even able to reliably detect very low hybrid EFs of up to 1 kV/m AC EF combined with 1 kV/m DC EF. This high sensibility, along with the synergistic effect of AC and DC, should be taken into consideration when assessing public reaction to the perception of EFs around hybrid overhead lines. In this context, the effect of environmental factors, such as relative humidity and ion currents, on the perception of low hybrid EFs could be investigated in future studies, as both factors were associated with lower detection thresholds⁸. Together with these findings, our data will help to prevent unwanted EF perception in nature and contribute to the construction of future hybrid overhead power lines.

Data availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

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Author contributions

K.J. and M.K. designed experiments and did data acquisition. T.Kram. technically monitored experiments. A.K. did medical examination of participants. K.J. did data analyses and interpretation. K.J. wrote the manuscript and A.K., T.Kram., T.Krau., and M.K. substantively revised the manuscript. All authors have approved the final version of the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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Erklärung § 5 Abs. 1 zur Datenaufbewahrung

Hiermit erkläre ich, dass die dieser Dissertation zu Grunde liegenden Originaldaten im Institut für Arbeits-, Sozial- und Umweltmedizin des Universitätsklinikums Aachen hinterlegt sind.

Erklärung gemäß § 5 Abs. (1) und (2), und § 11 Abs. (3) 12. der Promotionsordnung

Hiermit erkläre ich, **Kathrin Jankowiak**, an Eides statt, dass ich den wesentlichen Anteil an der Publikation:

Jankowiak, K., Drießen, S., Kaifie, A., Kimpeler, S., Krampert, T., Kraus, T., Stunder, D., and Kursawe, M. (2021). Identification of Environmental and Experimental Factors Influencing Human Perception of DC and AC Electric Fields. *Bioelectromagnetics*, 42(5), 341–356.
geleistet habe.

Die Anteile an der Arbeit waren wie folgt:

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Studiendesign		20					20	60	100
Med. Voruntersuchungen			100						100
Technische Unterstützung					50		50		100
Durchführung der Expositionsversuche								100	100
Datenaufbereitung und -auswertung	100								100
Interpretation der Datenauswertung	75							25	100
Verfassung des Manuskripts	100								100
Korrektur des Manuskripts		10	5	15	15	5	5	45	100

Aus diesem wesentlichen Anteil ergibt sich selbstverständlich die Stellung als Erstautorin.

Unterschrift der Doktorandin

Als Doktorvater und korrespondierender Autor bestätige ich die Angaben von Kathrin Jankowiak und in Vertretung für die Kooperationspartner.

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Ich schließe mich der Erklärung von Univ.-Prof. Dr. med. Thomas Kraus als Koautor an.

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Jankowiak, K., Kaifie, A., Krampert, T., Kraus, T., and Kursawe, M. (2022). The role of the AC component in human perception of AC-DC hybrid electric fields. *Scientific Reports*, 12. geleistet habe.

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Durchführung der Expositionsversuche	85				15	100
Datenauswertung	100					100
Interpretation der Datenauswertung	70				30	100
Verfassung des Manuskripts	100					100
Korrektur des Manuskripts		10	15	10	65	100

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